Mass Flux Concepts:

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The Netherlands

- ✓ **Mass flux approximations**
- ✓ **Entraining Plume model**
- ✓ **Mixing mechanisms**
- ✓ **Transition from shallow to deep convection**
- ✓ **Mass flux in the PBL and Boundary Layer**

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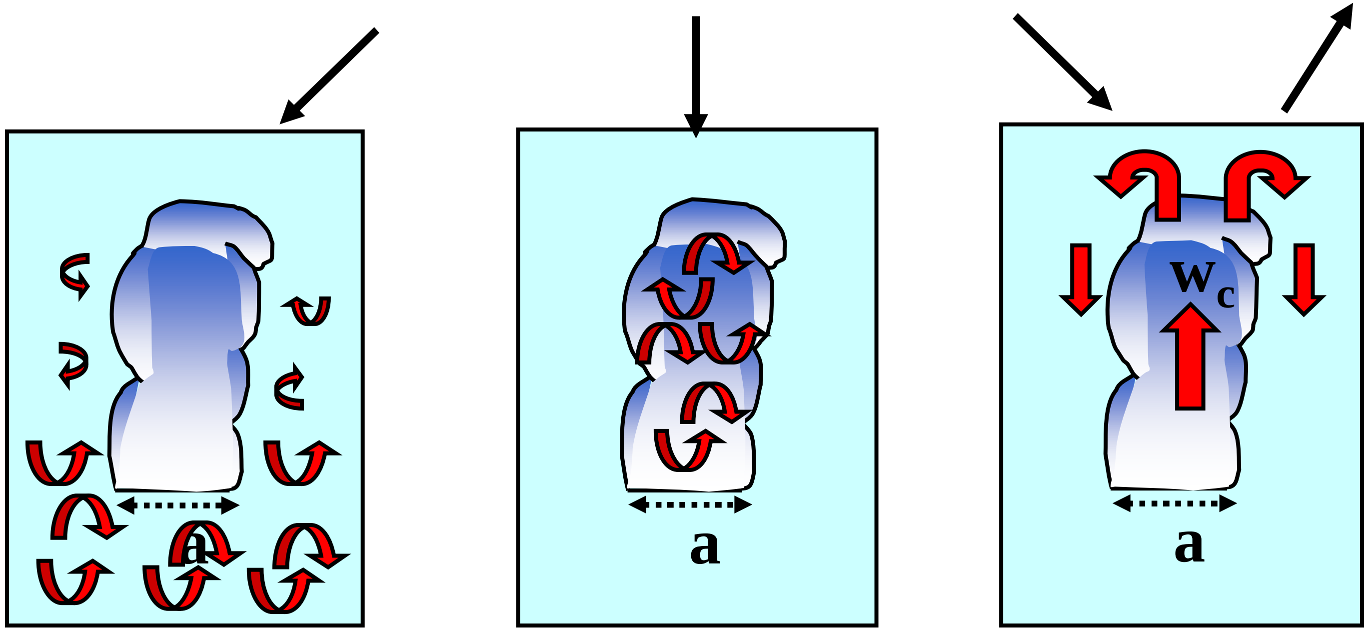
What is the mass flux concept?

Estimating (co)variances through smart conditional sampling of joint pdf's

$$\overline{w'\phi'} = (1-a)\,\overline{w'\phi'}^{e} + a\,\overline{w'\phi'}^{c} + a w_c(\phi_c - \bar{\phi}) \approx M(\phi_c - \bar{\phi})$$



Horizontal Variability

Why

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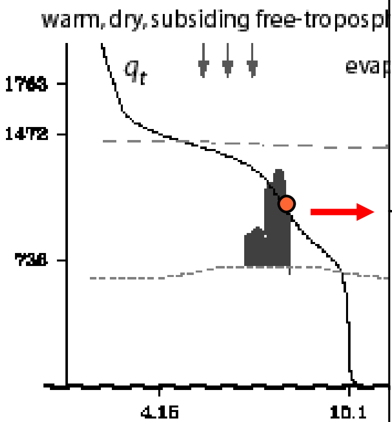
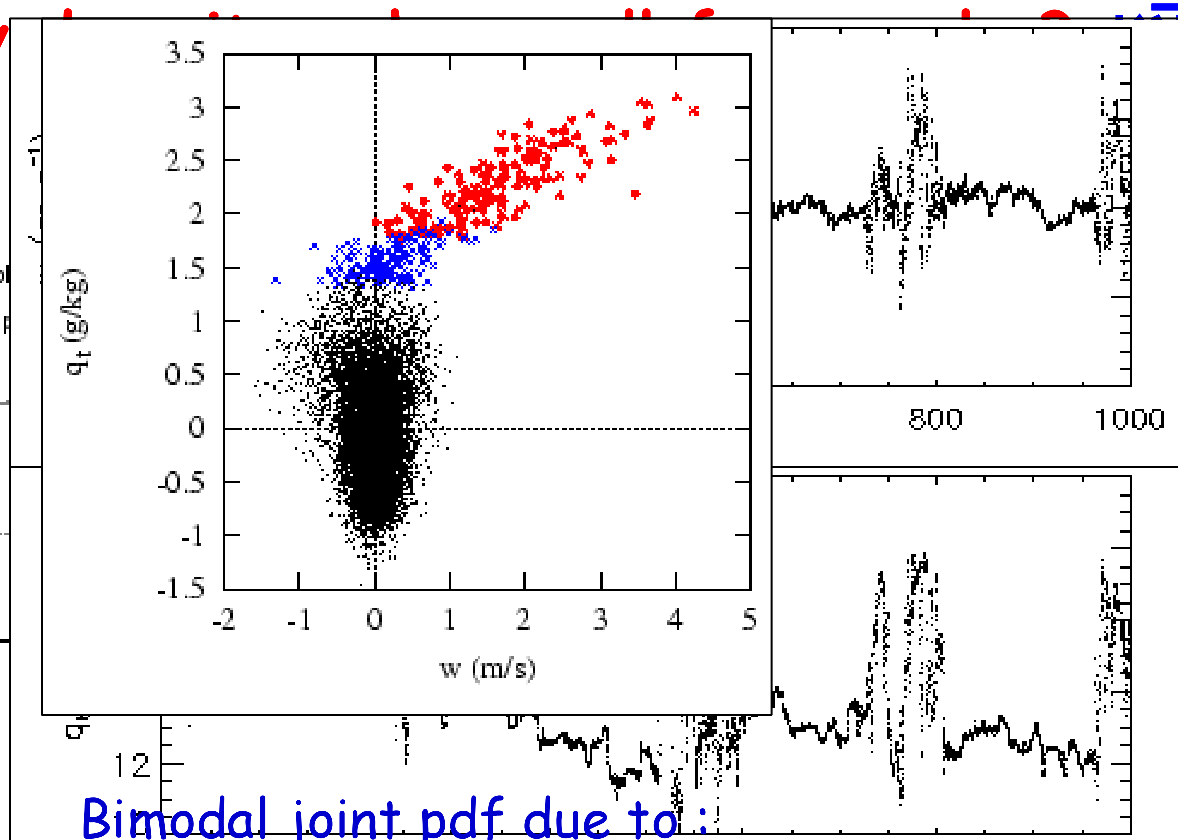


Courtesy : Bjorn Stevens



Bimodal joint pdf due to :

✓Buoyancy production by condensation in clouds (w)

✓Non-local transport (qt)

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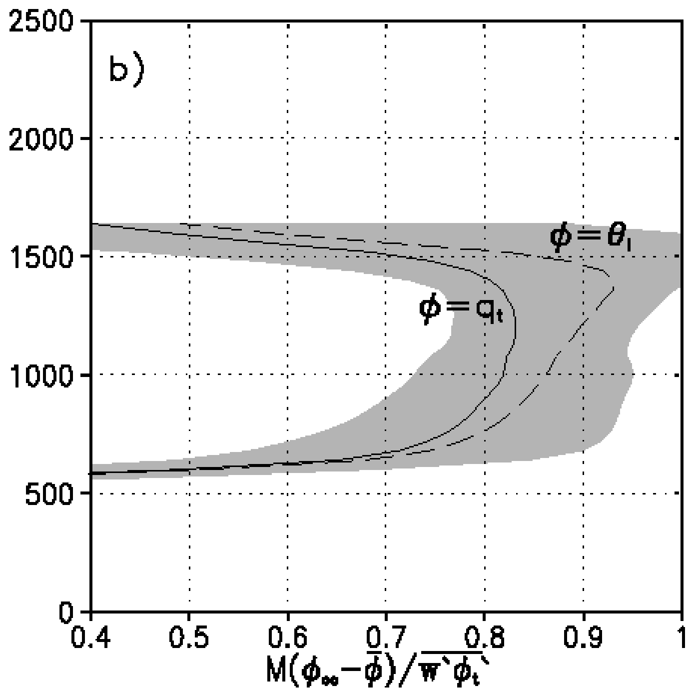

Cumulus: Typically 80~90% repesented for moist conserved variables by mass flux appr.

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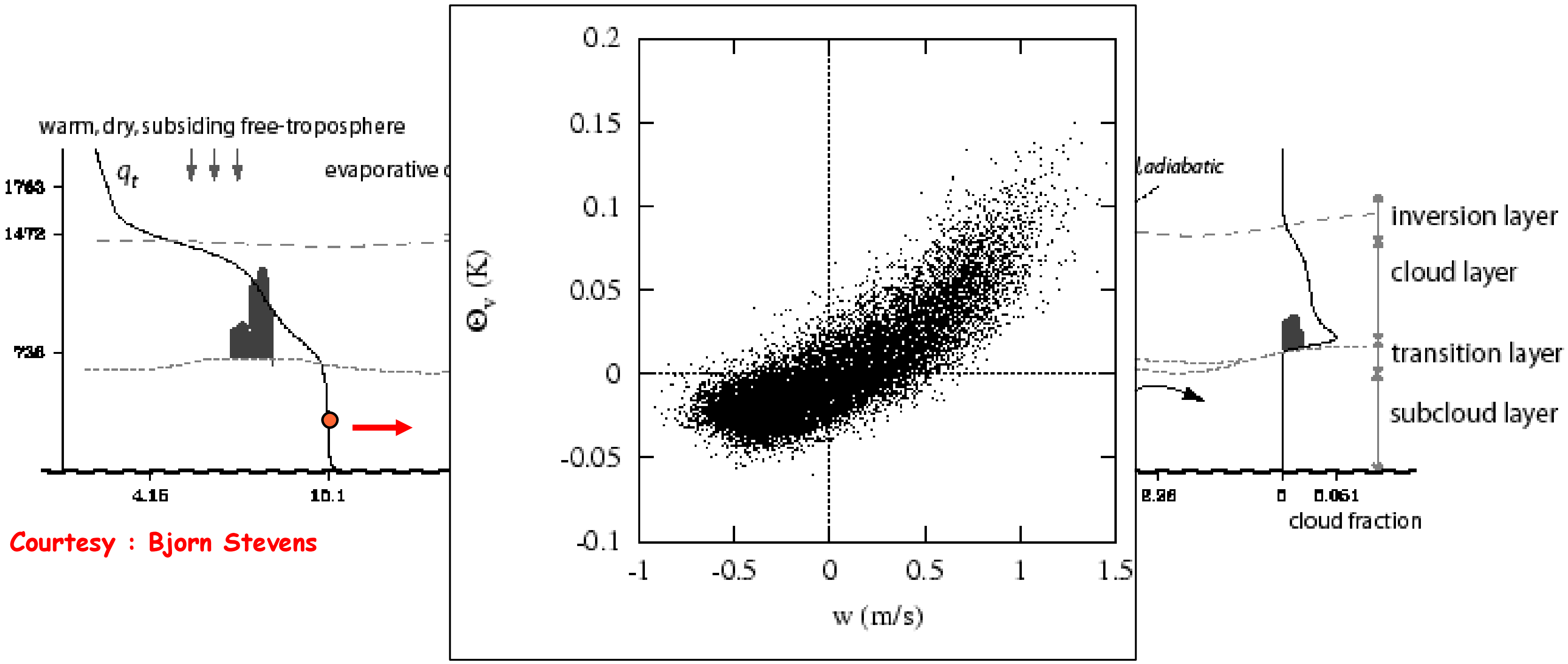
How well does it work for "dry" convection?



Courtesy : Bjorn Stevens

- ....

Assuming Joint Gaussian pdf and

using updraft/downdraft decomposition:

$$M\,(\phi_u - \phi_d) \approx 0.6\,\overline{w'\phi'}$$

- ....

Wyngaard&Moeng BLM 1992

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Remarks:

- Scu gives similar results for fluxes as dry convection (50~60%) when using updraft/downdraft.
(de Laat and Duynkerke BLM 1998)

- Deep Convection: Additional decomposition of cloudy downdrafts is advisable.

- Applying the same technique on variances and higher moments gives progressively worse results.

Health warning: Be careful by applying mass flux concept on variances, skewness and beyond.

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How to estimate updraft fields and mass flux?

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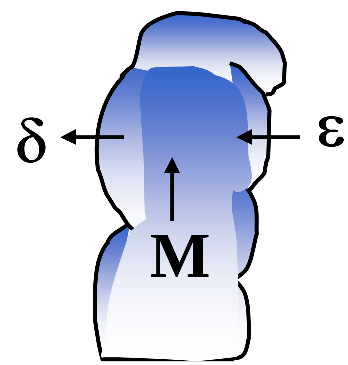
The old working horse:

Entraining plume model:

$$\frac{\partial \phi_c}{\partial z} = -\varepsilon(\phi_c - \overline{\phi}) \text{ for } \phi \in \{\theta_l, q_t\}$$

$$\frac{1}{M}\frac{\partial M}{\partial z} = \varepsilon - \delta$$

$$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = -b\varepsilon w_c^2 + aB$$



Plus boundary conditions at cloud base.

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Isn't the plume model in conflict with other proposed mixing mechanisms in cumulus?

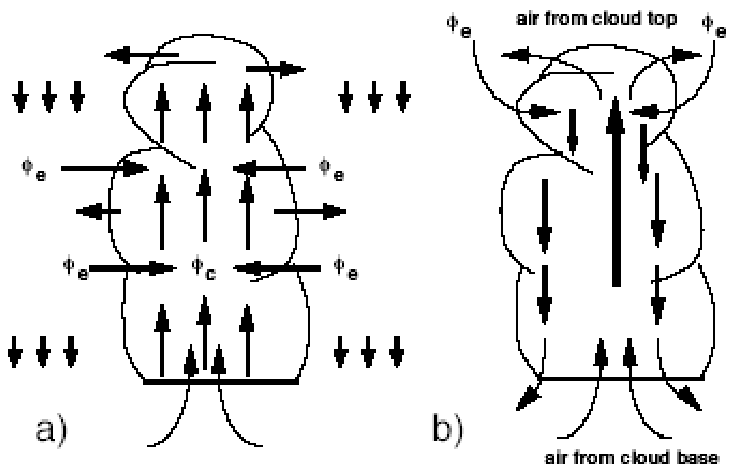

Figure 6. Schematic sketch of two extreme mixing mechanisms: a) *lateral mixing* where environmental air is continuously entrained into upward rising cloud air and b) *vertical mixing* where environmental air mixes with cloud air only near cloud base and cloud top.

Two-point mixing

Episodic mixing, etc.......

Pakuch 1979 JAS

Emanuel 1991 JAS

Blyth 80's

However: all these other concepts need substantial adiabatic cores within the clouds.

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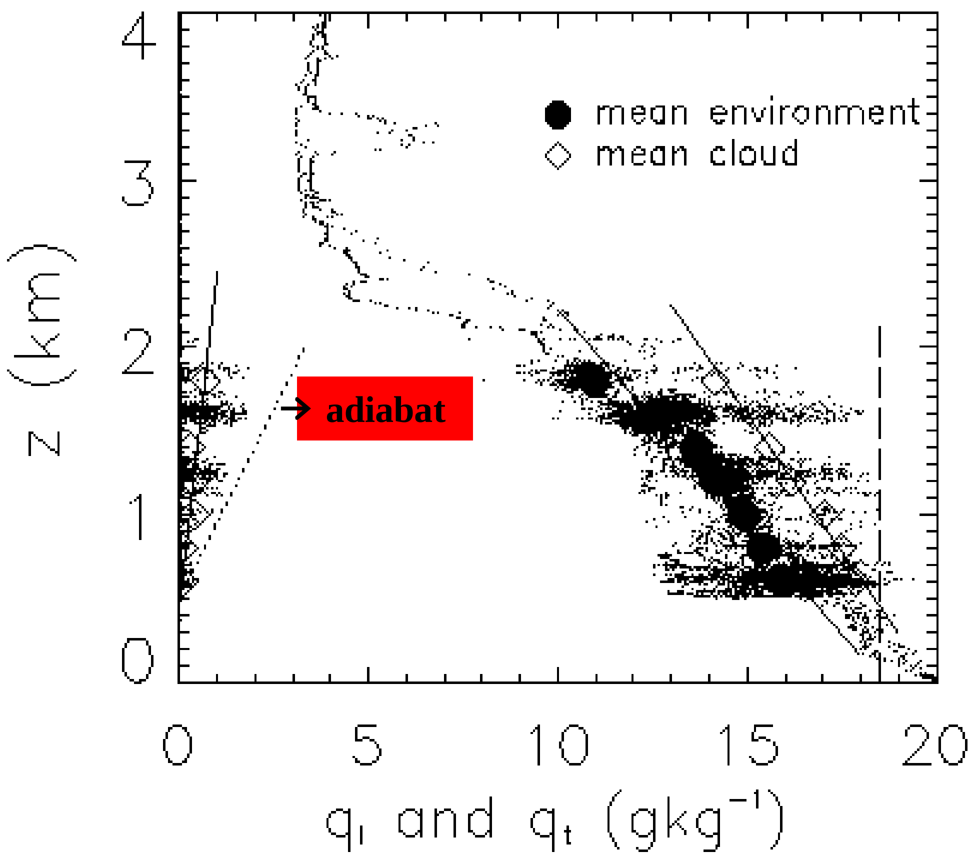
(SCMS Florida 1995)



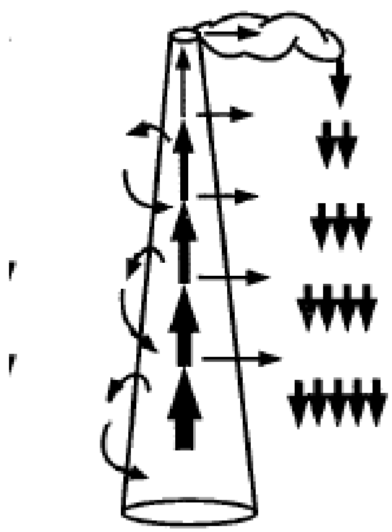
No substantial adiabatic cores (>100m) found during SCMS except near cloud base. (Gerber)

Does not completely justify the entraining plume model but………

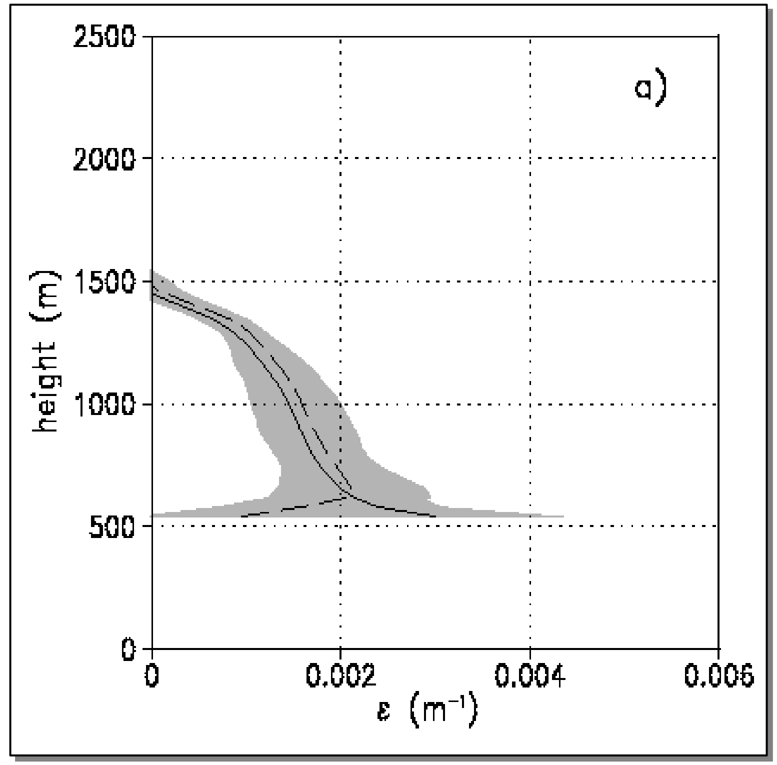
It does disqualify a substantial number of other cloud mixing models.

What is simplest entraining plume based parameterization?

Simply use diagnosed typical values for ε and δ based on LES and observations and suitable boundary conditions at cloud base (closure)



Trade wind cumulus: BOMEX

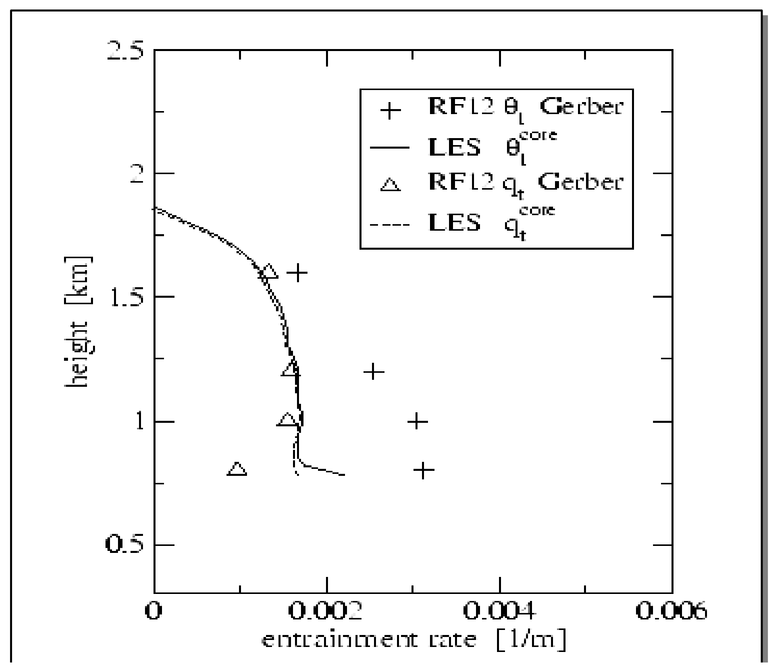


LES

$$\varepsilon = 1 \sim 3\ 10^{-3}\ \mathrm{m}^{-1}$$

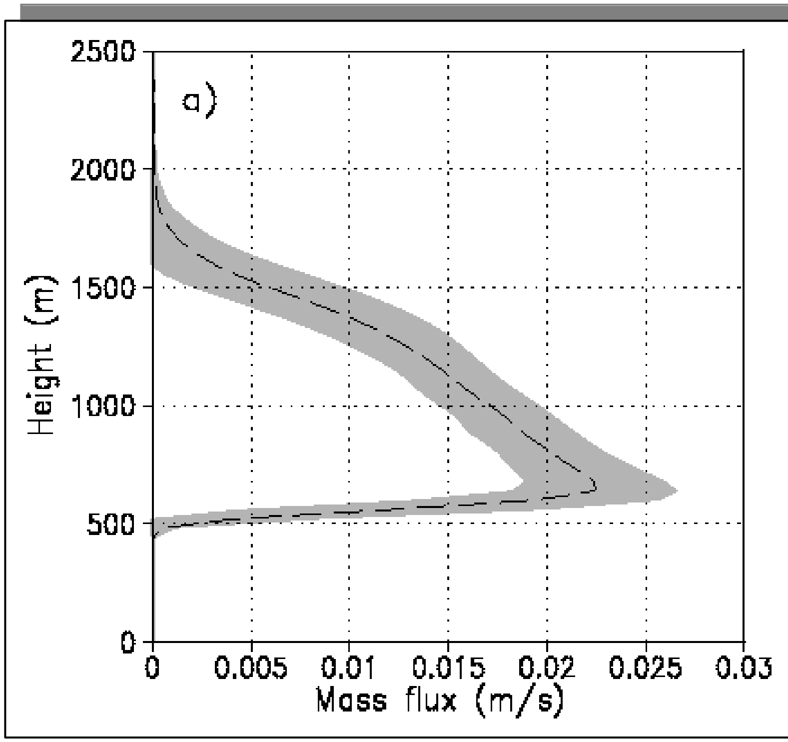
Observations

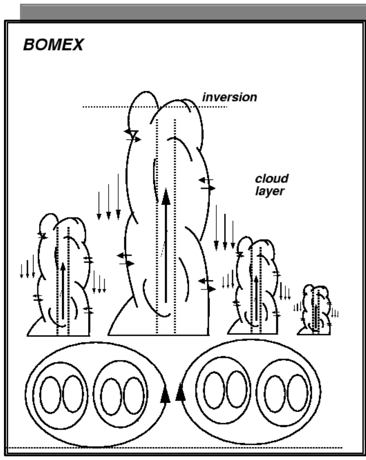
(Neggers et al (2003) Q.J.R..M.S.)



Cumulus over Florida: SCMS

•Mass Flux





$$M = a_c w_c$$

Diagnose δ using M and ε

$$\frac{1}{M}\frac{\partial M}{\partial z} = \varepsilon - \delta$$

$$\delta = \varepsilon + 0.5\ 10^{-3}$$

Works reasonably well for shallow cumulus:

BOMEX: Siebesma et al JAS 2003

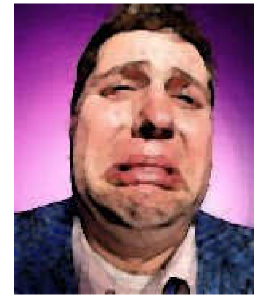
ARM: Brown et al QJRMS 2002

SCMS: Neggers et al QJRMS 2003

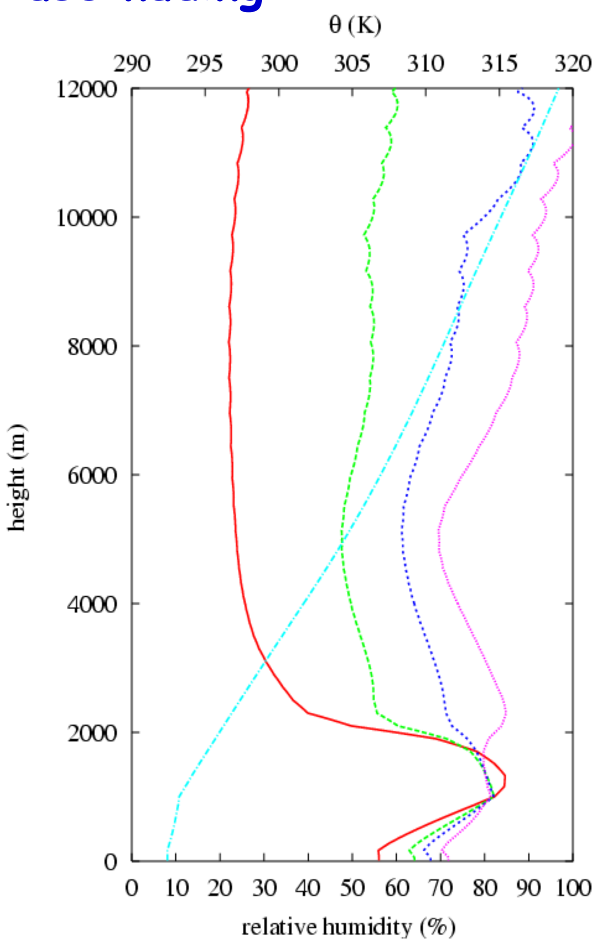
ATEX: Stevens et al JAS 2001

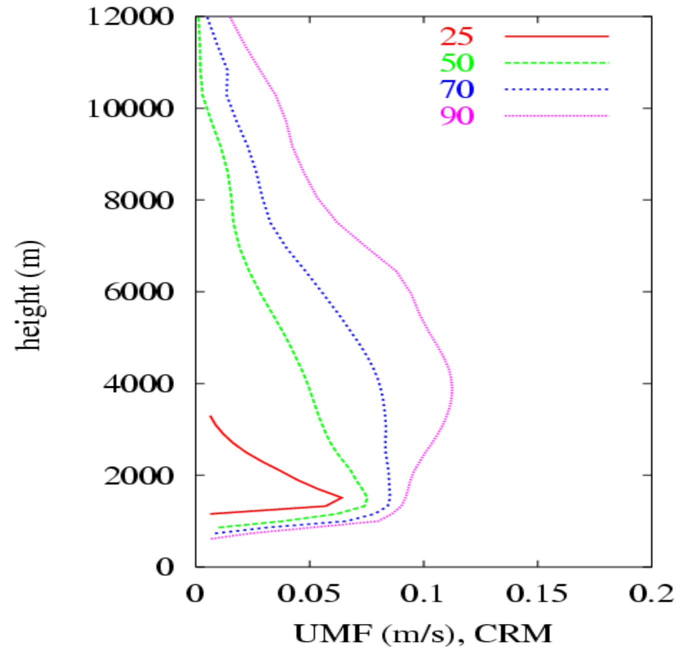
But does it work for deep(er) convection ....

Derbyshire et al, QJRMS 2004 EUROCS special issue



4 cases:
RH=25%,50%,70% 90%
Same θ–profile
use nuding





Steady State Mass flux profiles of CRM's!!

ε and δ change with environmental conditions so a more flexible approach is required!!

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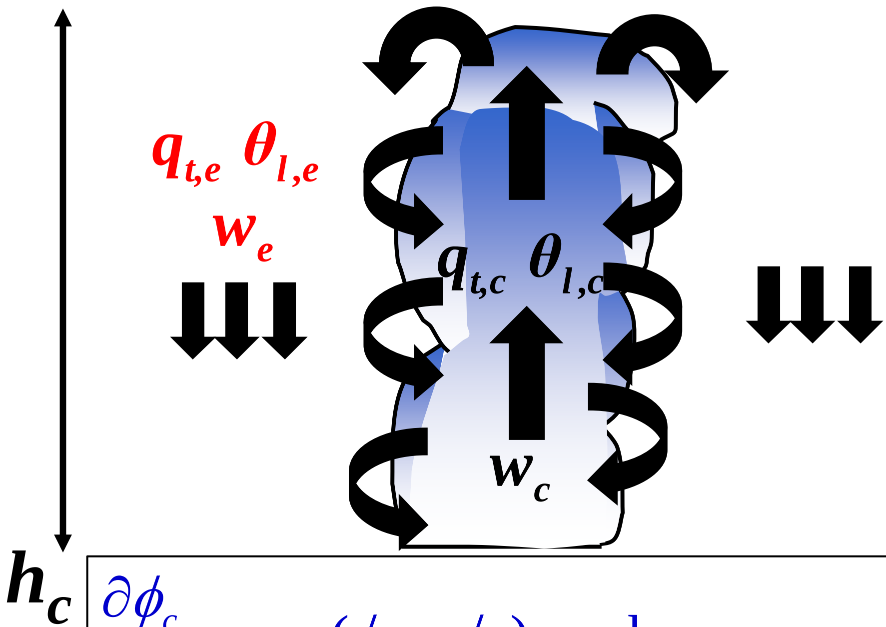
Simplest conceptual model for entrainment



$$for\ \phi \in \{\theta_l, q_t\}:$$

$$\frac{d\phi_c}{dt} = F_{mixing}$$

$$w_c \frac{\partial \phi_c}{\partial z} = -\frac{(\phi_c - \phi_e)}{\tau}$$

$$\frac{\partial \phi_c}{\partial z} = -\varepsilon(\phi_c - \phi_e) \quad \text{where} \quad \varepsilon = \frac{1}{w_c \tau} \approx \frac{1}{h_c}$$

Siebesma 1997

Bretherton and Grenier JAS 2003

Shallow convection: $h_c \sim 1000$m

$\varepsilon \sim 10^{-3}\ m^{-1}$!!

Alternative: $$\varepsilon \approx \frac{1}{w_c \tau_0} \propto \frac{1}{w_c}$$

Neggers et al 2001 JAS

Cheinet 2003 JAS

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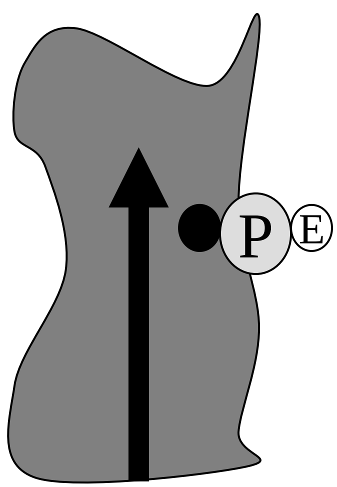
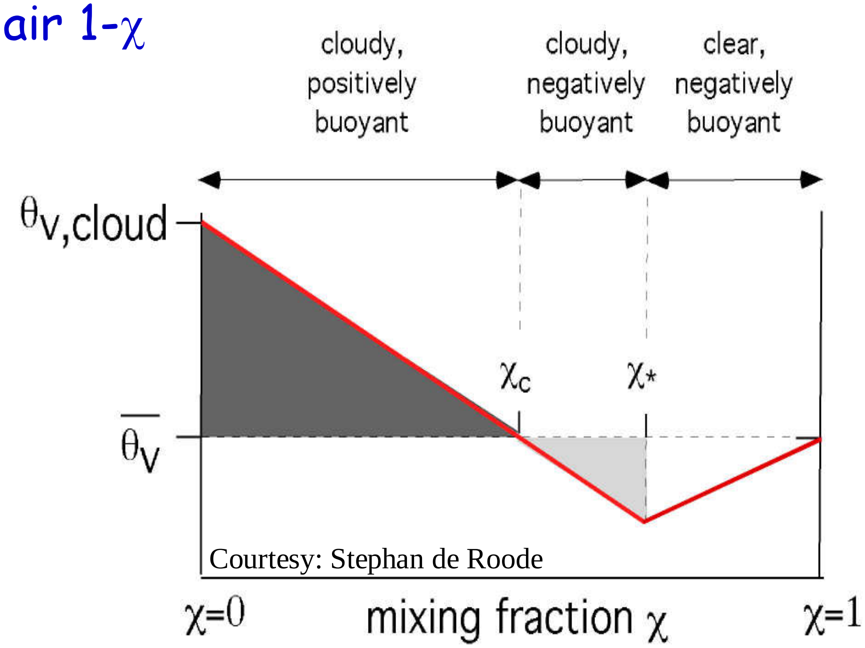
But how about detrainment? (or, the mass flux?)

Kain-Fritsch buoyancy sorting scheme (1991) is the only scheme to my knowledge that makes a prediction of ε and δ

The periphery of a cloud consists of air parcels that have distinct fractions environmental air χ and cloudy air 1-χ





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Buoyancy sorting mixing principle

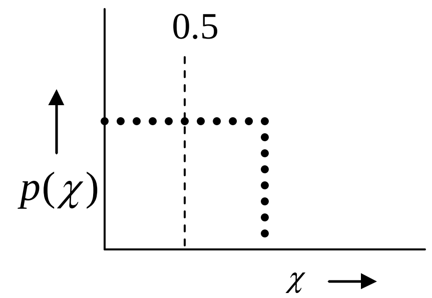
The mixed parcels have distinct probabilities of occurrence $P(\chi)$

Specify an inflow rate ε_0 **M**

Assume the simplest PDF (Bretherton and Grenier (2003):

$$E = 2\varepsilon_0 M_u \int_0^{\chi_c} \chi p(\chi) d\chi = \varepsilon_0 M_u \chi_c^2 .$$

$$D = 2\varepsilon_0 M_u \int_{\chi_c}^{1} (1-\chi) p(\chi) d\chi = \varepsilon_0 M_u (1-\chi_c)^2 .$$



use:

$$E = \varepsilon M \qquad D = \delta M$$

$$\Rightarrow \quad \varepsilon = \varepsilon_0 \chi_c^2 , \qquad \delta = \varepsilon_0 (1-\chi_c)^2 .$$

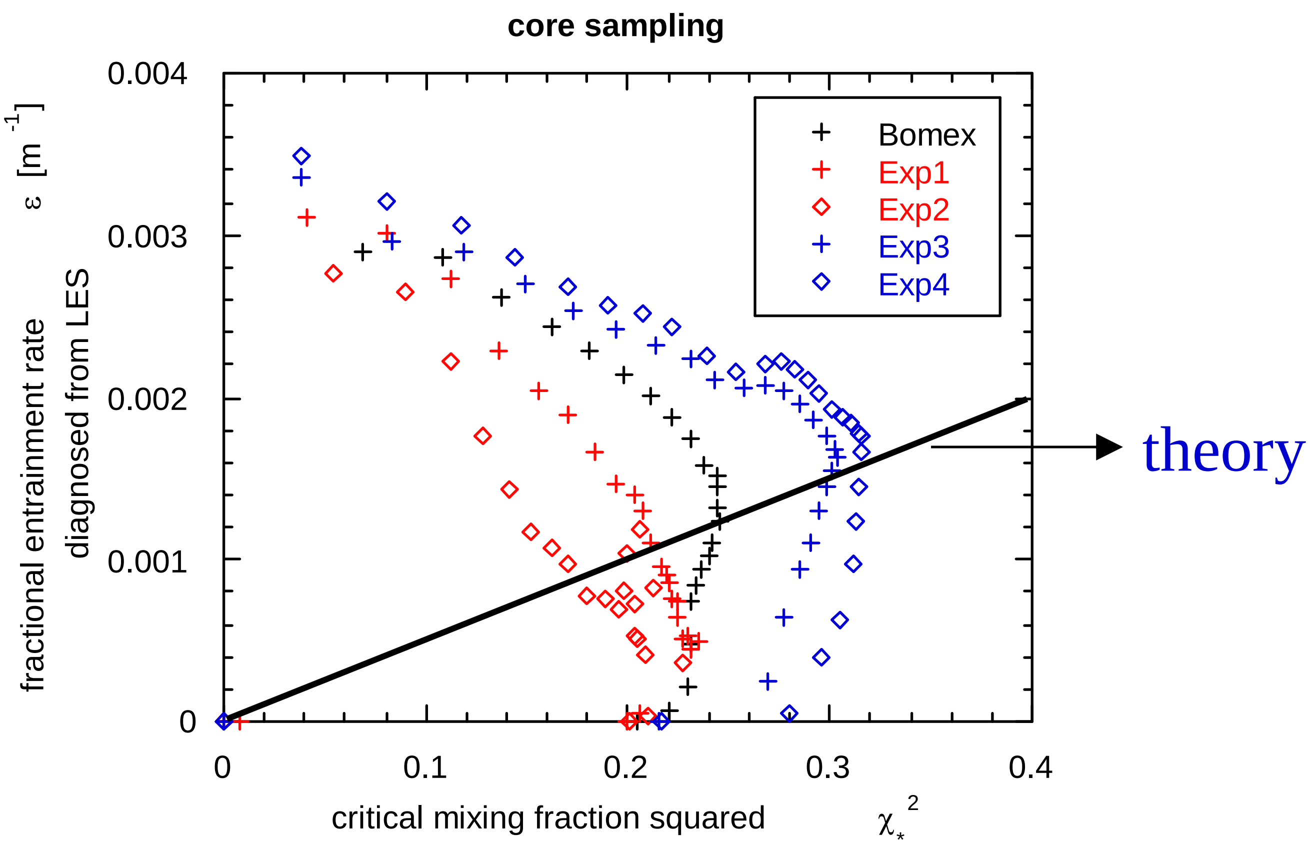
Remark: if $\chi_c < 0.5$ then : E<D => dM/dz < 0

if $\chi_c > 0.5$ then : E>D => dM/dz > 0

Parameterization: $\varepsilon = \varepsilon_0 \chi^2$

Does it work? Check from LES results.

ε_{LES}



ε_0 = 5e-3 m-1

χ^2_c

•••• Another Avenue to derive Mass flux M:

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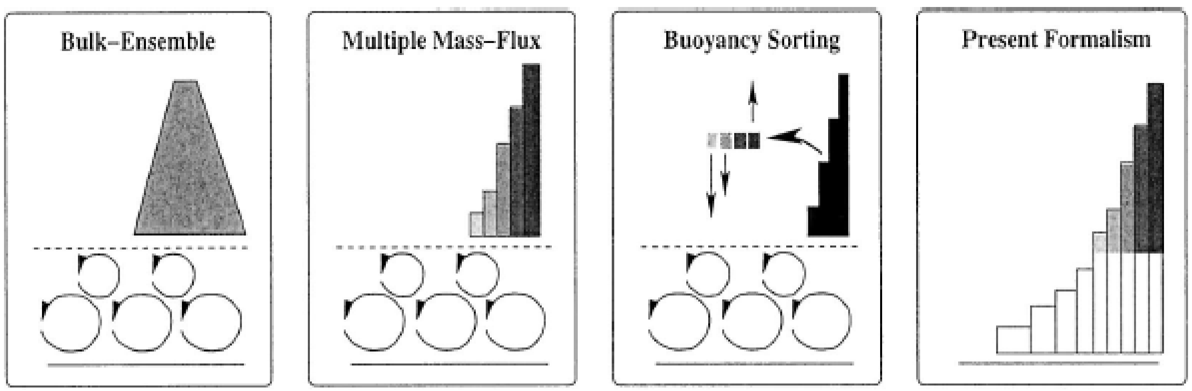
$$M \equiv a_c w_c = \frac{1}{N}\sum_i w_{c,i}$$

Multiple Mass Flux Parameterization

Arakawa Schubert JAS 1974

Neggers et al. JAS 2001

Cheinet JAS 2003

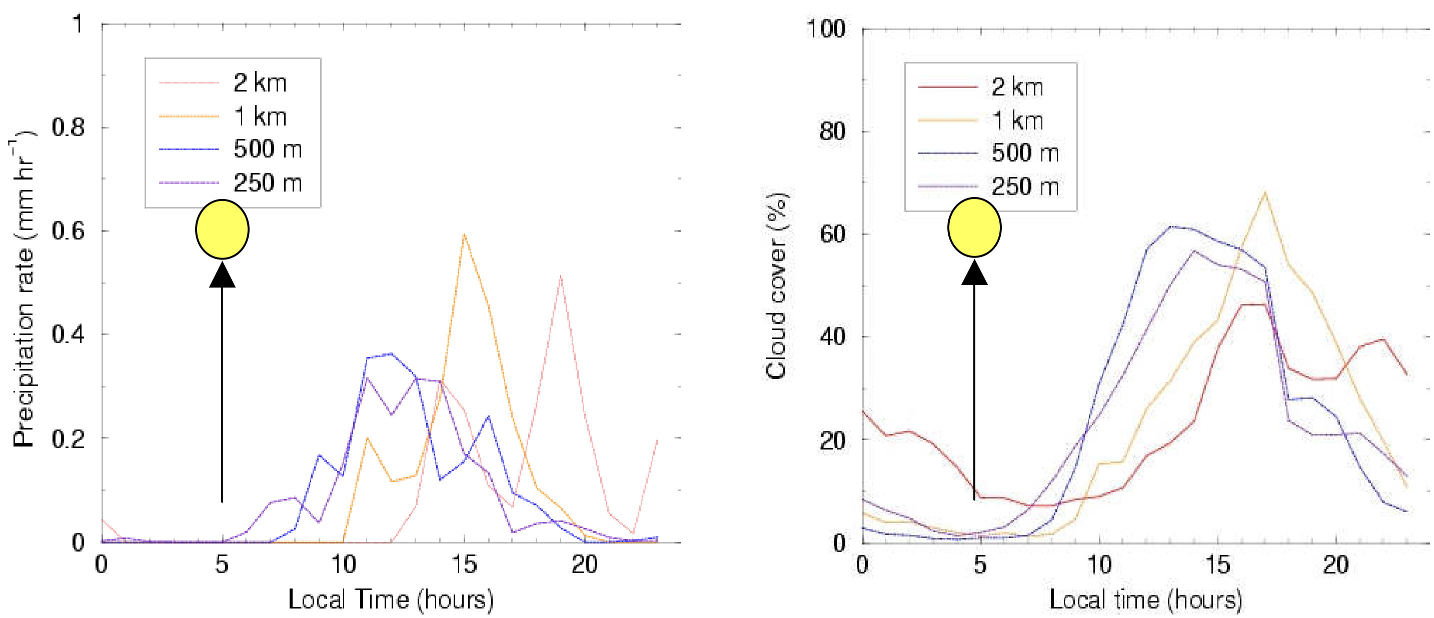


•••• Works good for shallow convection but……

only gives decreasing mass flux

Can mass flux parameterize transition from shallow to deep convection?

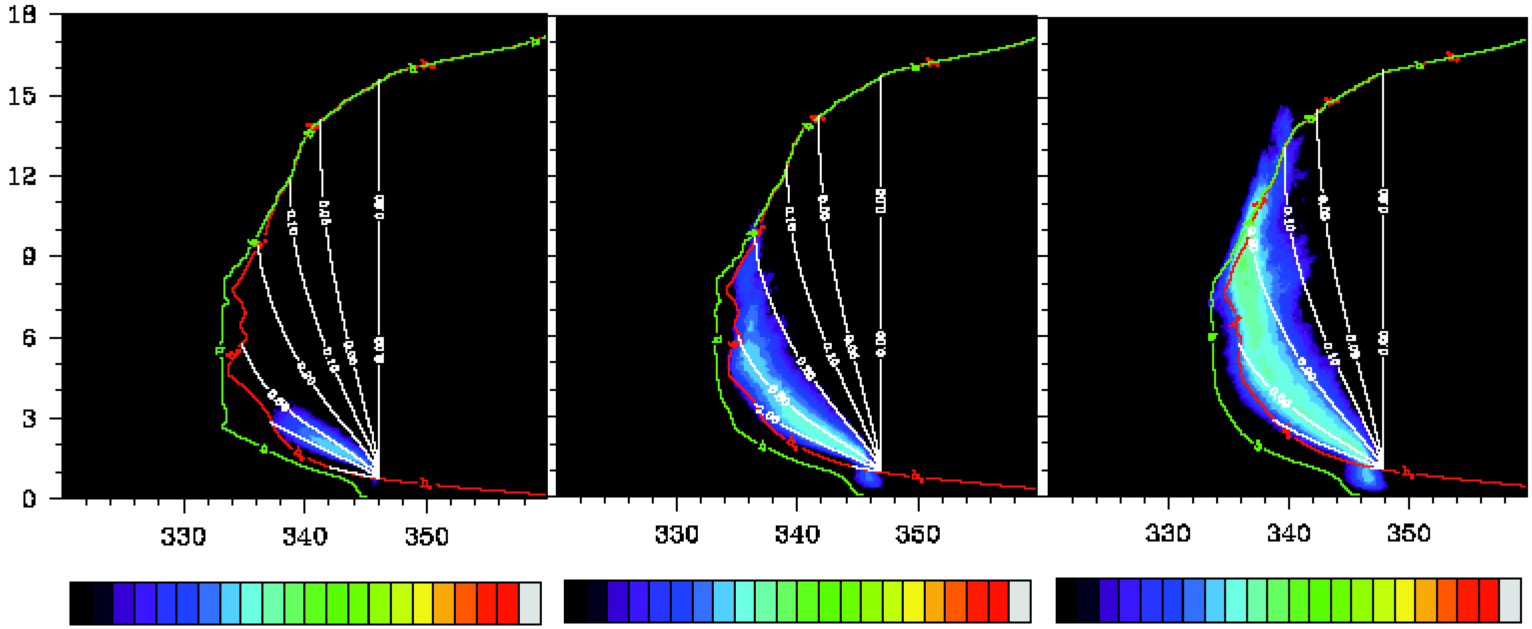
- Deep Convection mass flux parameterization in the tropics starts to precipitate hours too early within the diurnal cycle
- CRM studies suggest this is related to a slow transition from shallow to deep convection



Thanks to Jon Petch (Met office) (QJRMS 2004 EUROCS special issue)

PDF of moist static energy in updraft cores (w >3 m/s)

4 h 5 h 6 h



log(pdf)

$$\frac{\partial}{\partial z}\eta h = \lambda \eta \overline{h}$$

$$\frac{\partial \eta}{\partial z} = \lambda \eta$$

PDF of moist static energy at updraft cores at various times from a high-resolution simulation of shallow-to-deep convection transition based on the TRMM-LBA observations over Amazonia.
Various curves on the plots are: mean moist static energy (green), mean saturated moist static energy (red), and entraining-plume trajectories (white) with numbers indicating the values of the corresponding entrainment parameter of the entraining-plume model (left) .
The simulation was done with the CSU System for Atmospheric Modeling (SAM).
Domain size was 1536 x 1536 x 256 with 100 m horizontal and variable vertical resolution (50 m in PBL).
Marat Khairoutdinov, 2005

Is this the end of the classic Entraining Plume Model?

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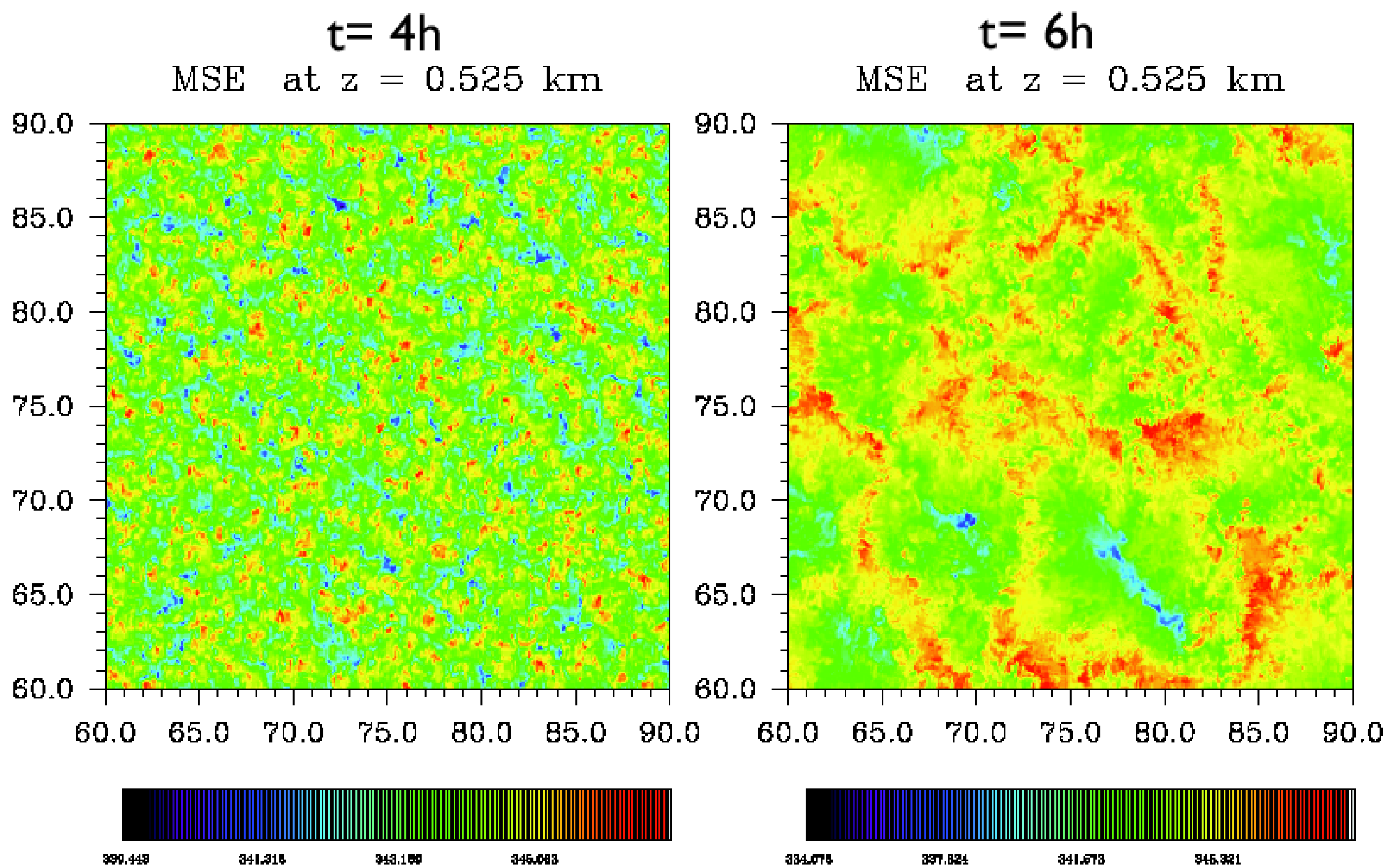

During early stage of the day: small scale structures in the pbl that trigger small strongly entraining cumulus clouds with limited vertical extend

During later stage of the day: larger scale structures in the pbl trigger larger cloud structures that entrain less and reach higher cloud tops.

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Attemps to unify convective transport in clear, subcloud and cloud layer

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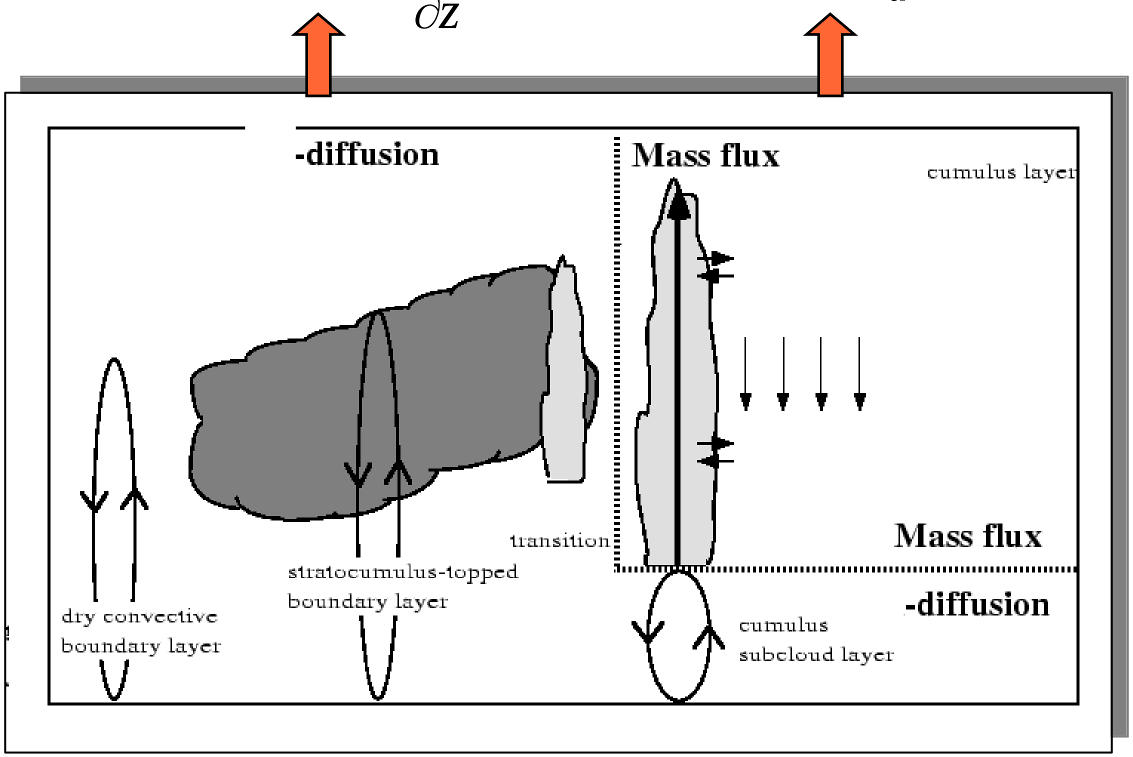
Standard parameterization approach:

$$\overline{w'\phi'} \cong -K\frac{\partial\overline{\phi}}{\partial z} \qquad \overline{w'\phi'} \cong M(\phi_u - \overline{\phi}) \qquad \frac{\partial\overline{\phi}}{\partial t} \cong -\frac{\partial}{\partial z}\left(\overline{w'\phi'}\right) + \overline{S}$$



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This unwanted situation has led to:

- Double counting of processes
- Interface problems
- Problems with transitions between different regimes

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Three roadmaps:

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1. **Only Eddy Diffusivity** *(Bechtold et al. JAS **52** 1995)*

2. **Only Mass Flux** *(Cheinet JAS 2003)*

3. **Both Mass Flux and Eddy Diffusivity**

(Siebesma and Teixeira : AMS Proceedings 2000)

*(Lappen and Randall. JAS **58** 2001)*

*(Soares et al., QJRMS, **130** 2004)*

••••*(Siebesma et al. submitted to JAS)*

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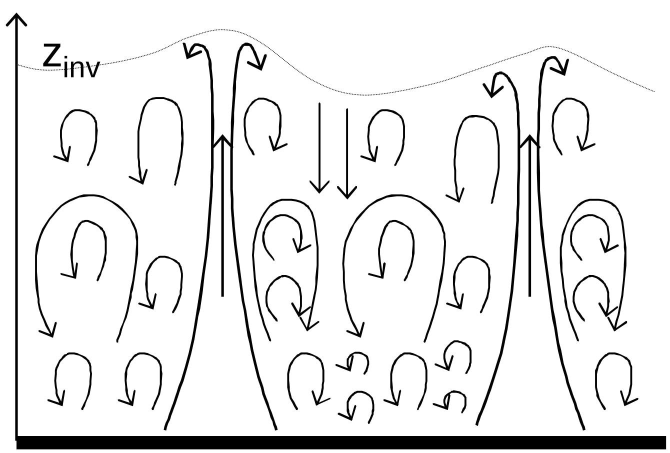
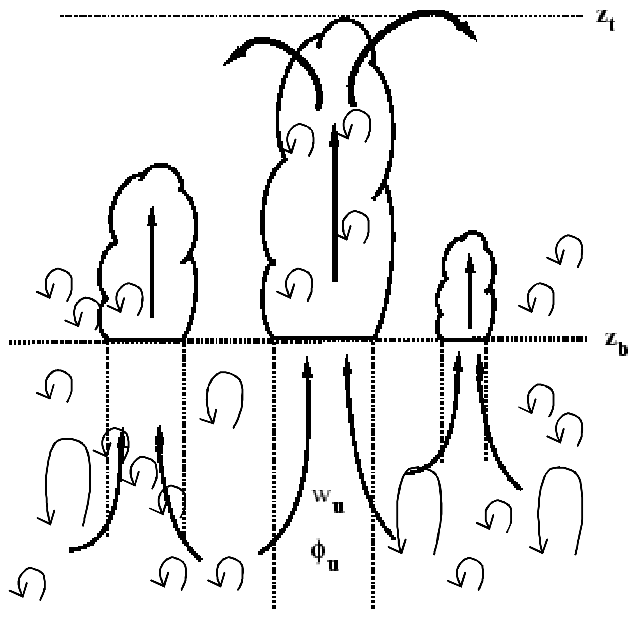
Extending the plume model to the subcloud layer.

The Idea :

- **Nonlocal (Skewed) transport through strong updrafts in clear and cloudy boundary layer by advective Mass Flux (MF) approach**

- **Remaining (Gaussian) transport done by an Eddy Diffusivity (ED) approach**





Motivation

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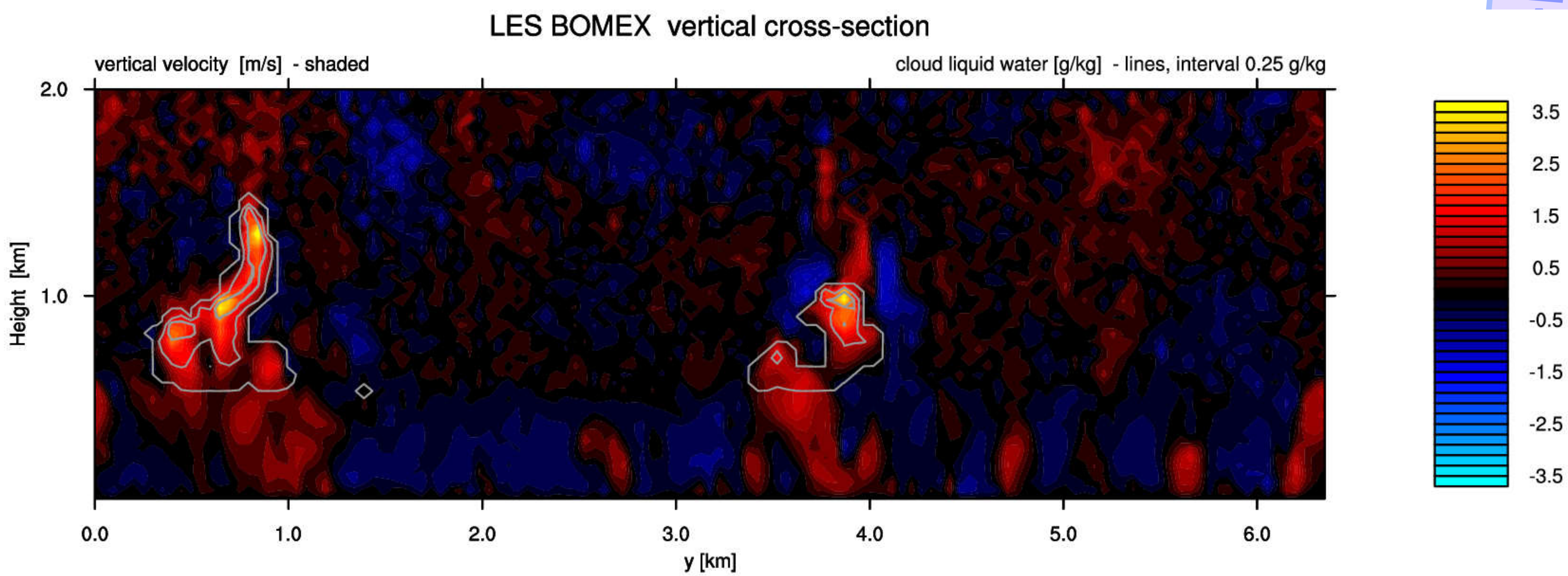
LES results on shallow cumulus

Barbados Oceanographic and Meteorological Experiment (BOMEX)



Strongest updrafts: are always cloudy
root deeply into the subcloud layer

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Advantages :

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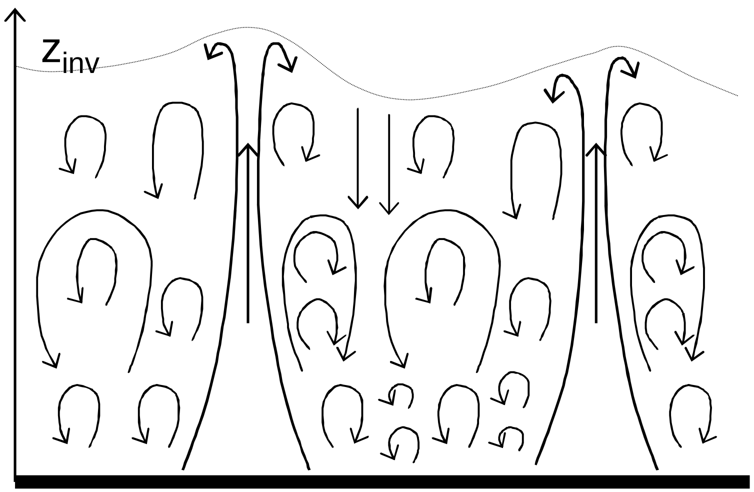
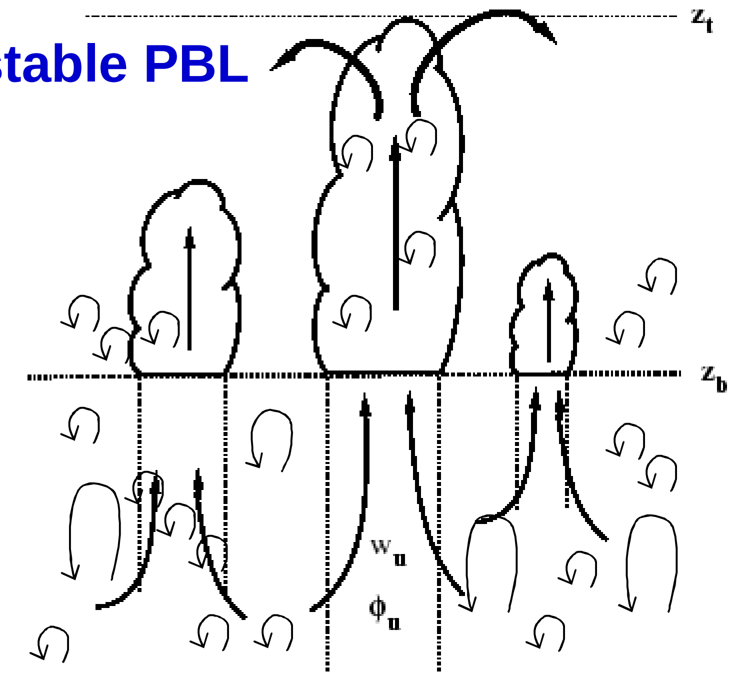
•One updraft model for : dry convective BL, subcloud layer, cloud layer.

•No trigger function/closure for moist convection needed

•No switching required between moist and dry convection needed

•Easy transition to neutral and stable PBL





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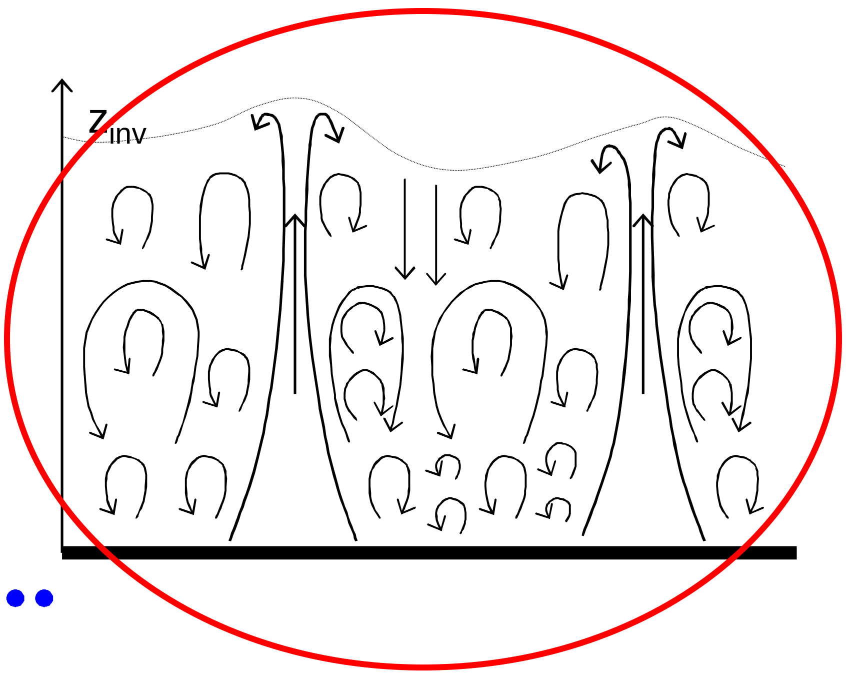
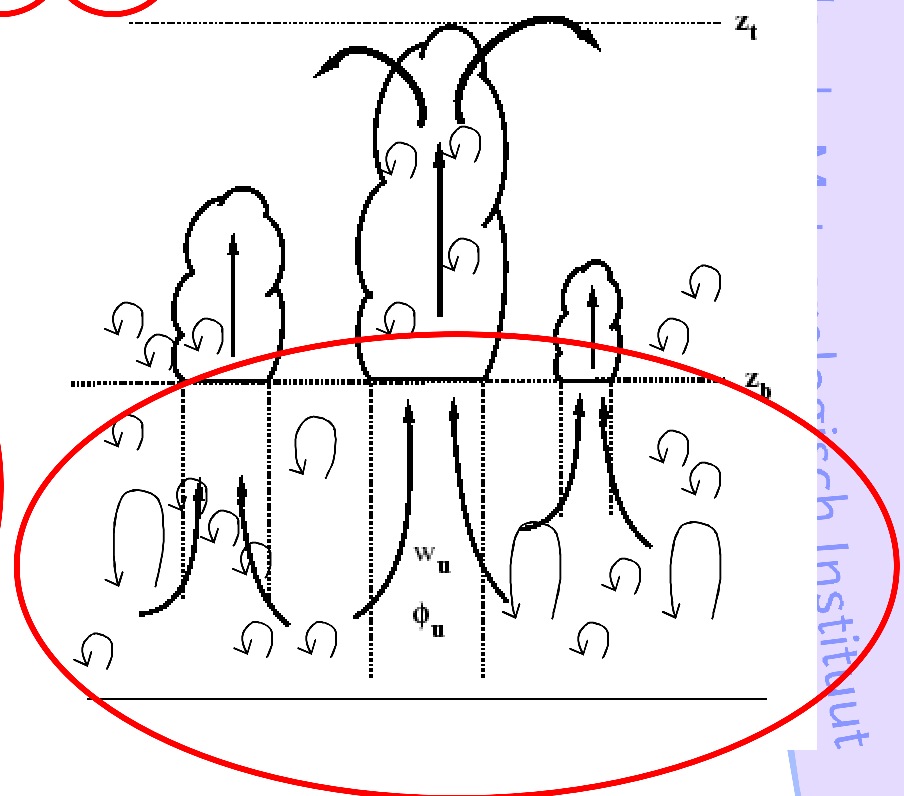
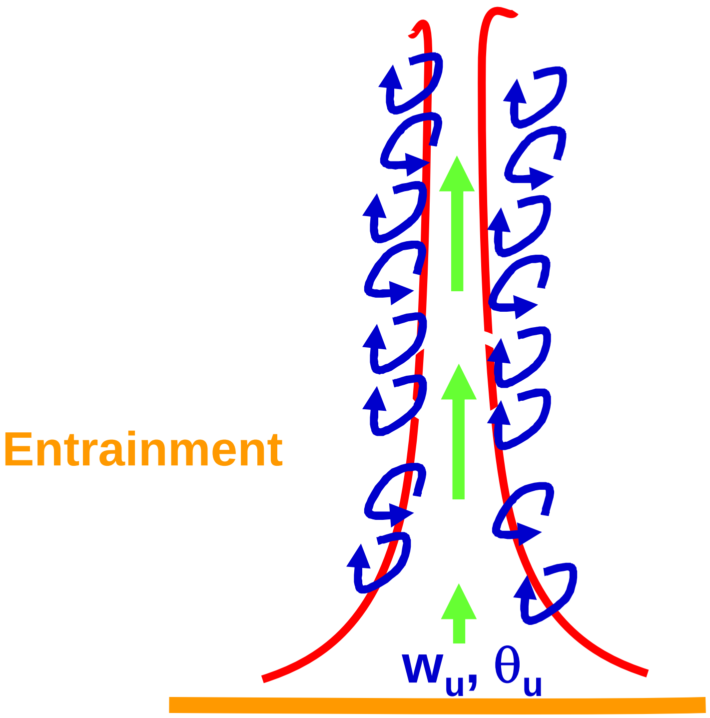
The Parameterization of the Eddy Diffusivity-Mass Flux (ED-MF) approach

$$\overline{w'\phi'} \cong -K\frac{\partial\overline{\phi}}{\partial z} + M(\phi_u - \overline{\phi})$$





Steady State Updraft Equations



Initialisation of updraft eq.?

Entraining updraft parcel:

$$\frac{\partial \theta_u}{\partial z} = -\varepsilon\left(\theta_u - \bar{\theta}\right)$$

ε: Fractional entrainment rate:

Vertical velocity eq. of updraft parcel:

$$w_u \frac{\partial w_u}{\partial z} = -\varepsilon_w w_u^{\,2} + \frac{g}{\theta_0}(\theta_{v,u} - \bar{\theta}_v) - \frac{1}{\rho}\frac{\partial p}{\partial z}$$

$$\ldots\ldots\ldots = -\varepsilon_w w_u^{\,2} \quad + \quad B \quad - \quad P$$

advection **entrainment** **buoyancy** **pressure**

Use LES to derive updraft model in clear boundary layer.

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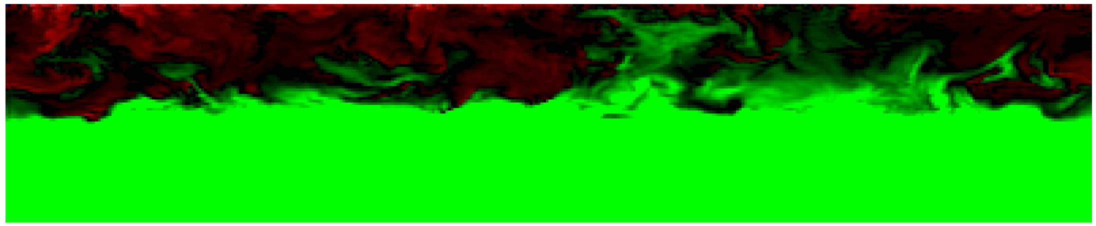

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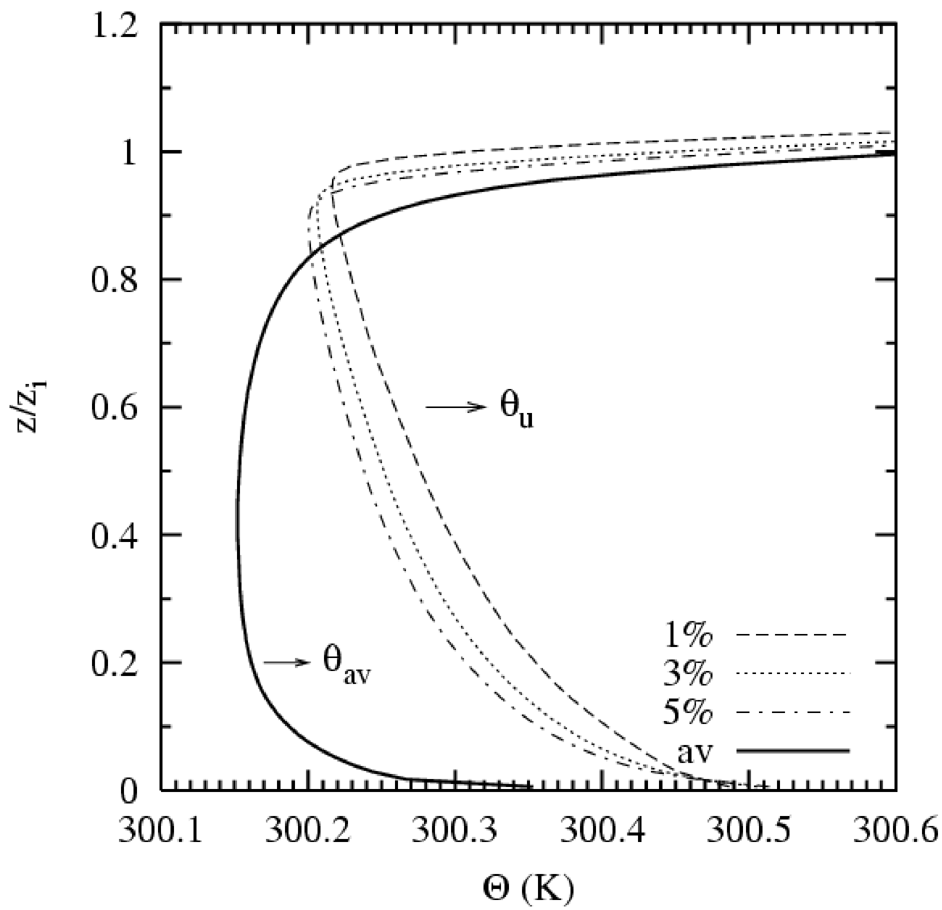

Updraft at height z composed

of those grid points

that contain the highest p%

of the vertical velocities:

p=1%,3%,5%:

Use LES results to diagnose entrainment ε

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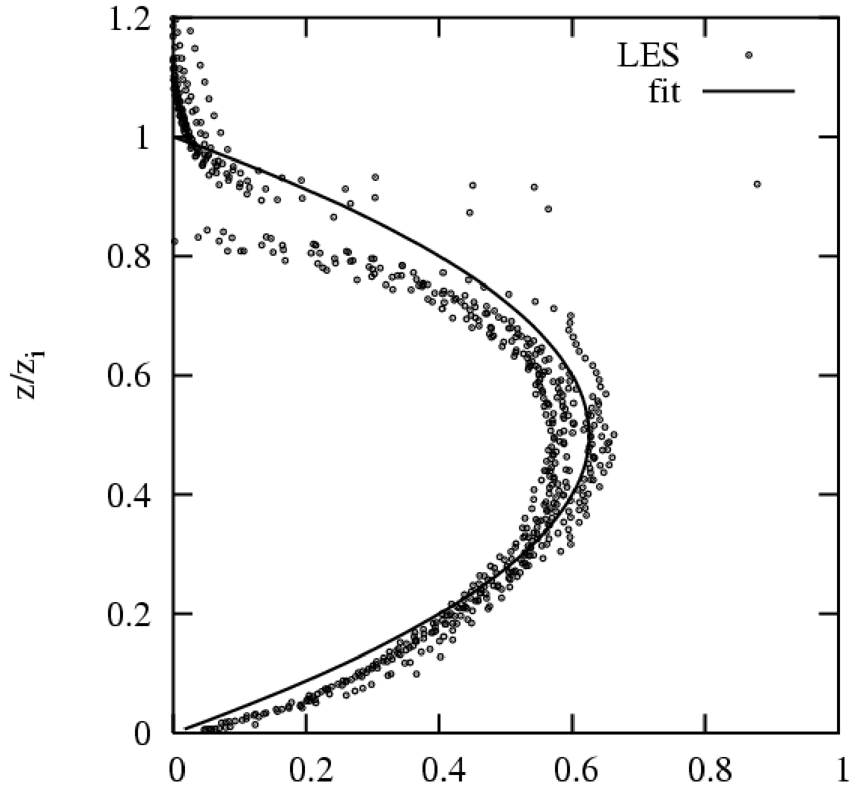
From LES

$$\varepsilon = -\frac{\partial \theta_{lu}}{\partial z} / \left(\theta_{lu} - \overline{\theta}_l \right)$$

Fit:

$$\varepsilon = c_e \left(\frac{1}{z} + \frac{1}{z_i - z} \right)$$

$$\cong 1 / w_u \tau$$



$1/\varepsilon z_i$ →

Remark : ε high near interfaces and low in the middle of the pbl

Remark:. 1/ε has similar behaviour has length scale formulations in TKE sche

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Use LES results to diagnose vertical velocity budget

$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = -\varepsilon_w w_u^{\ 2} \quad + \quad B \quad - \quad P$$

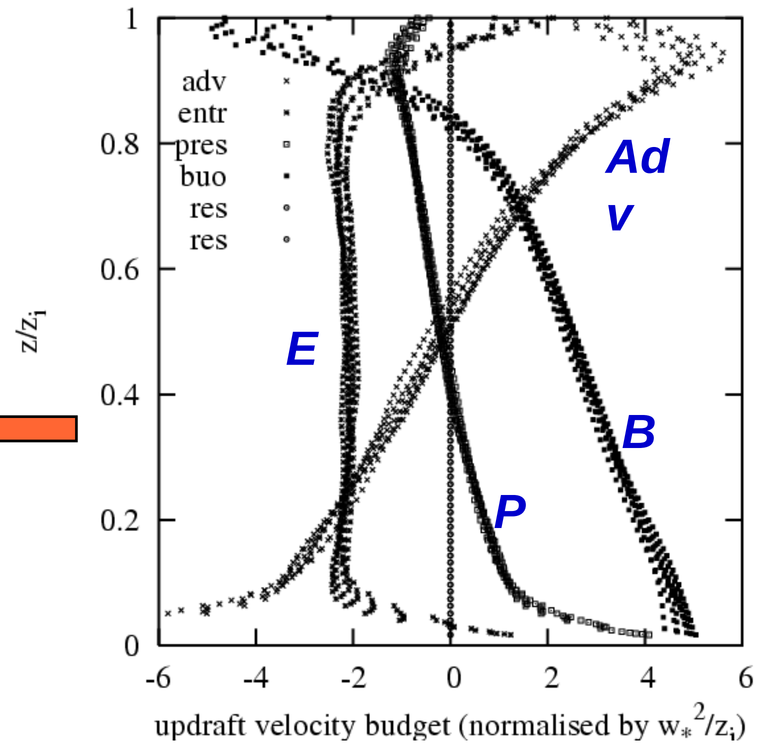
$$P = -\frac{\partial \overline{w^2}}{\partial z} \cong -\frac{\partial \mu \overline{w_u^2}}{\partial z} \qquad \mu \approx 0.15$$

$$\varepsilon_w \approx b\varepsilon \qquad b \approx 0.5$$

$$\frac{1}{2}(1-2\mu)\frac{\partial w_u^2}{\partial z} = -\varepsilon_w w_u^{\ 2} + B$$

Similar format as Simpson (1969)

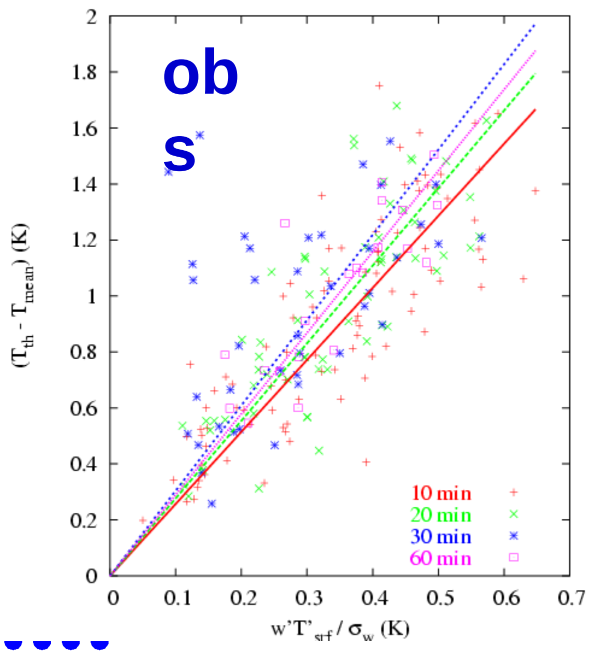
w_u-budget:

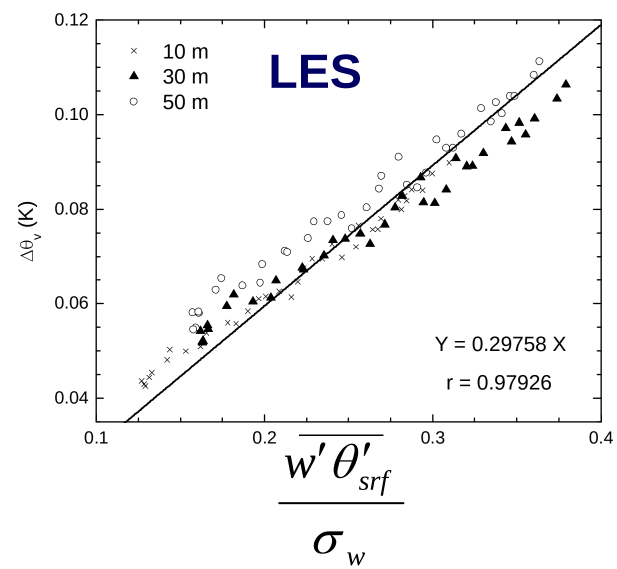


Initialisation of the updraft

Initialise updraft at lowest model layer: $\theta_u = \bar{\theta} + \Delta\theta$

With an excess that scales with the Surface flux (Troen and Mahrt 1986): $$\Delta\theta = \alpha \frac{\overline{w'\theta'_{srf}}}{\sigma_w} \qquad \alpha \approx 1 \sim 2$$





Eddy Diffusivity:

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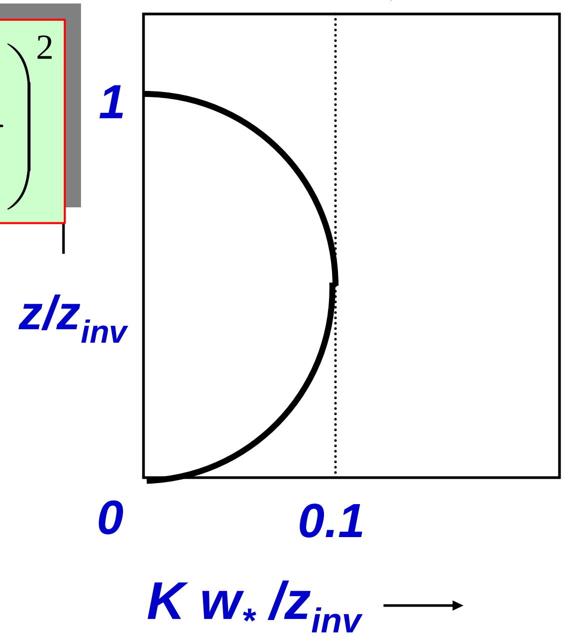
K-profile:

$$K \equiv k\left(u_*^3 + 39 k w_*^3 \frac{z}{z_i}\right)^{1/3} z \left(1 - \frac{z}{z_i}\right)^2$$

Holtslag 1998



Mass flux:

$$M \equiv a_u w_u$$

$a_u = 0.03$

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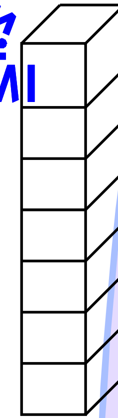
Single Column Model tests for convective BL



Only Diffusion: ***ED***

$$\overline{w'\theta'} = -K\frac{\partial\overline{\theta}}{\partial z}$$

Diffusion + Mass Flux:
ED-MF

$$\overline{w'\theta'} = -K\frac{\partial\overline{\theta}}{\partial z} + M\,(\theta_u - \overline{\theta})$$

Diffusion + Counter-Gradient: ED-CG

$$\overline{w'\theta'} = -K\frac{\partial\overline{\theta}}{\partial z} + K\gamma$$

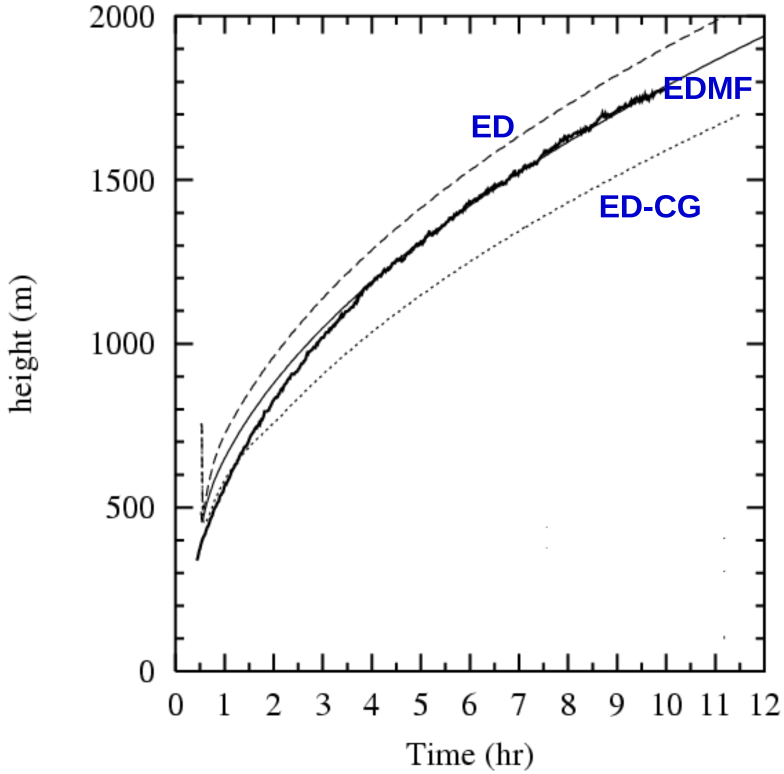
Solve

$$\frac{\partial\overline{\theta}}{\partial t} = -\frac{\partial\overline{w'\theta'}}{\partial z}$$

with implicit solver ***(Teixeira 2000)***

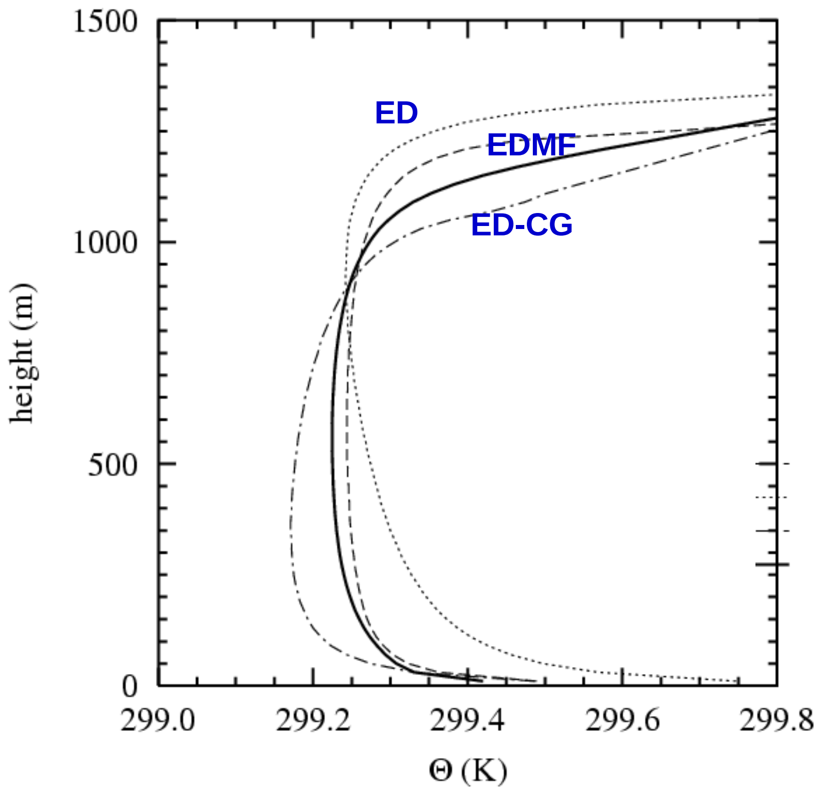
• • • •

BL-growth



PBL height growth

Mean profiles after 10 hours



Mean profile

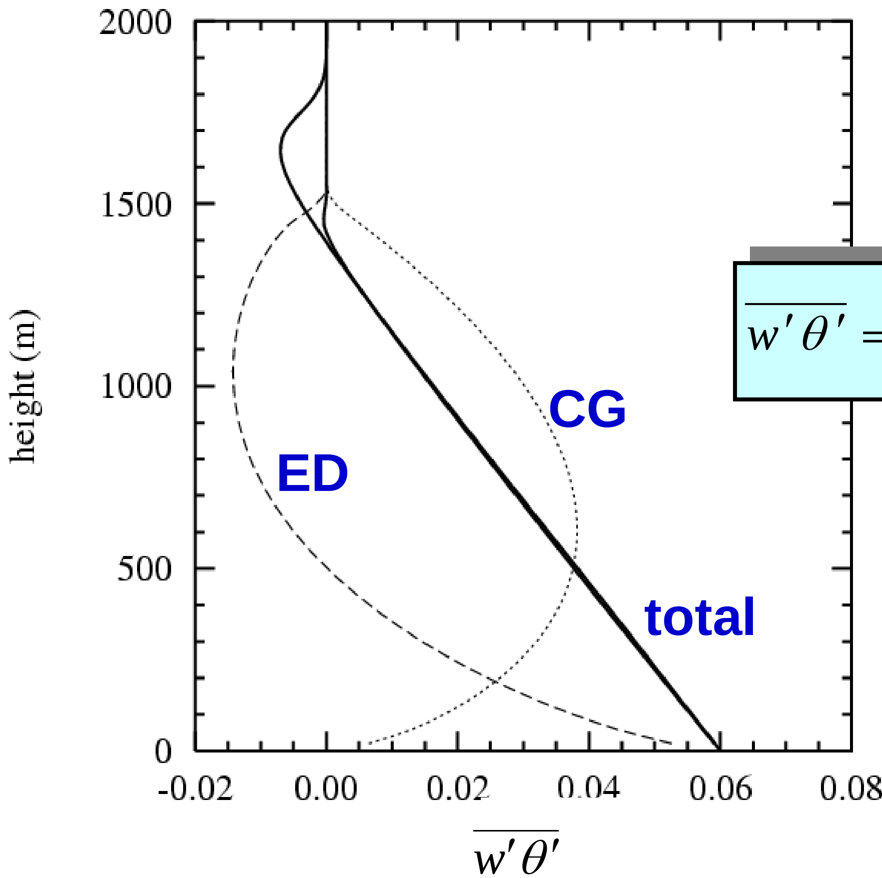
ED : Unstable Profiles : Too aggressive top-entrainment : too fast pbl -growth

Counter-gradient: Hardly any top-entrainment : too slow pbl-growth.

Howcome??

KNMI

Breakdown of the flux into an eddy diffusivity and a countergradient contribution



$$\overline{w'\theta'} = -K\frac{\partial\overline{\theta}}{\partial z} + K\gamma$$

No entrainment flux since the countergradient (CG) term is balancing the ED-term!!

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Conclusions

ED MF provides good frame work for integral turbulent mixing in CT -PBL

- ***Correct internal structure***
- ***Correct ventilation (top-entrainment) for free atmosphere***
- ***Easy to couple to the cumulus topped BL***

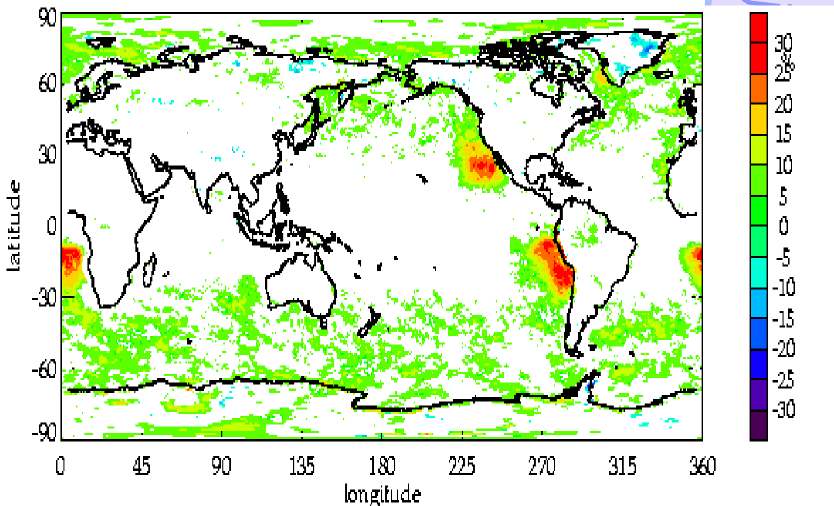
Countergradient approach

- ***Correct internal structure but…..***
- ***Underestimation of ventilation to free atmosphere***
- ***Cannot be extended to cloudy boundary layer***

Two flavours of ED-MF now implemented in operational models

1. **ECMWF : K-profile ED + Mass**

Roel Neggers and Martin Kohler



Impact on low cloud cover

2. **Meso-NH Model : TKE-closure based ED + Mass Flux**

Pedro Soares and coworkers (*QJRMS*, **130** 2004) ***(special EUROCS issue)***

Matching with convection scheme through $M_b = a_u w_u$ (similar to Grant closure)

••••

Other important untouched Topics

KNMI

- **Momentum transport** (Brown 1998 QJRMS, Lappen and Randall submitted
- **Triggering** *(Bechtold)*
- **Transition scu ⇔ cu**
- **Equilibrium Solutions** *(Stevens. Grant)*

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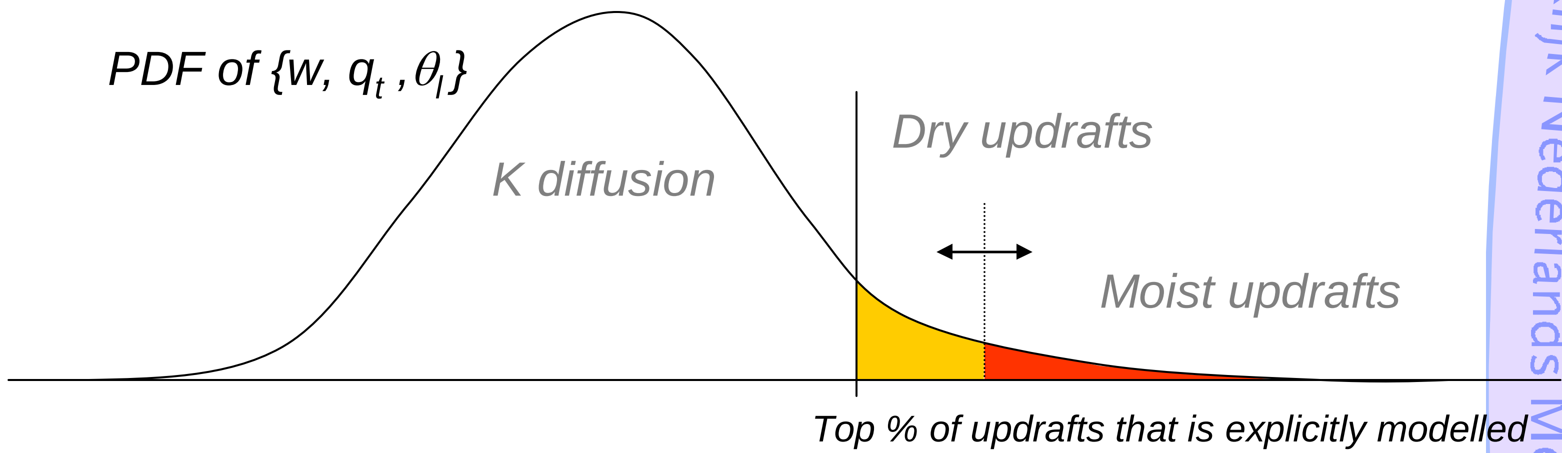
A statistical mass flux framework for organized updrafts

KNMI

Each updraft corresponds to a certain fraction of the joint PDF



Model each fraction's averaged internal statistics

- *vertical integration of updraft budget equations*
- *updraft initialization depends on its position in the PDF*

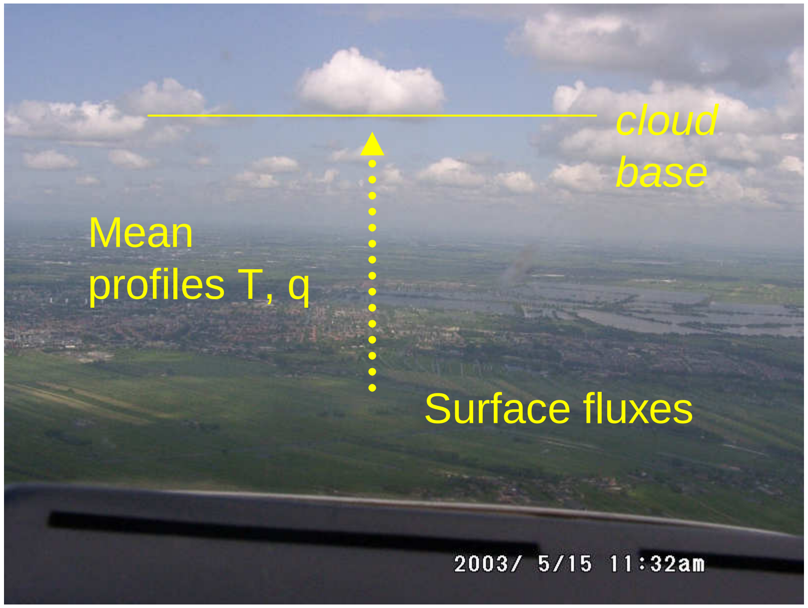
The moist area fraction is a free variable

- *closure is done on the area fraction instead of on the mass flux as a whole* $M_i \equiv a_i w_i$
- *a flexible area fraction can act as a 'soft trigger function' (dry ⟷ moist transition)*

Extensively tested against observations in Cabauw

(Marijn de Hay)

Estimate cloud convective properties on the basis of observations in sub-cloud layer



Courtesy Manfred Wendisch, IfT Leipzig

Properties:

- Presence of BL clouds
- Cloud base(/top) height
- In-cloud properties

(LWC, vertical velocity)

Sensitivity study (1)

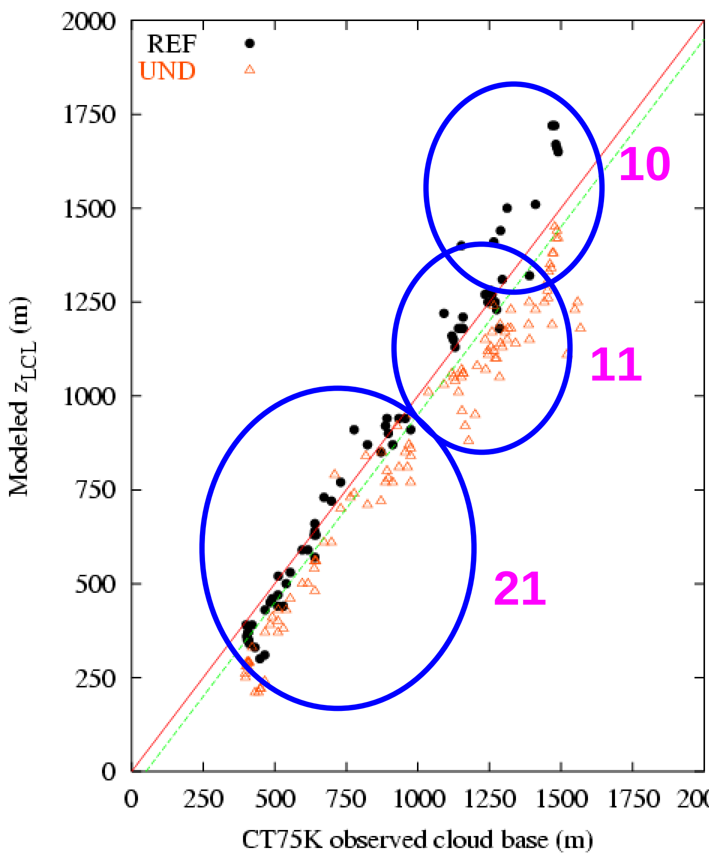
Sensitivity to dilution

30-60 m bias in Vaisala CT75 cloud base (red to green)

Lateral mixing:

- suppresses cloud presence
- causes higher cloud base

UND run undershoots cloud base, in some cases better with REF but great variability

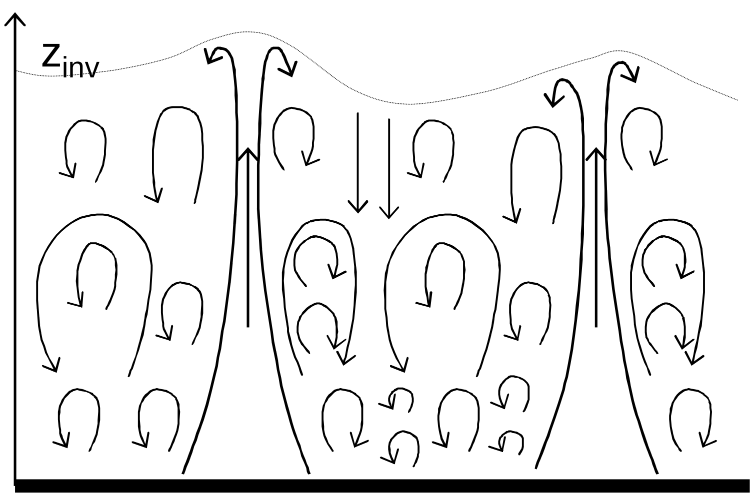


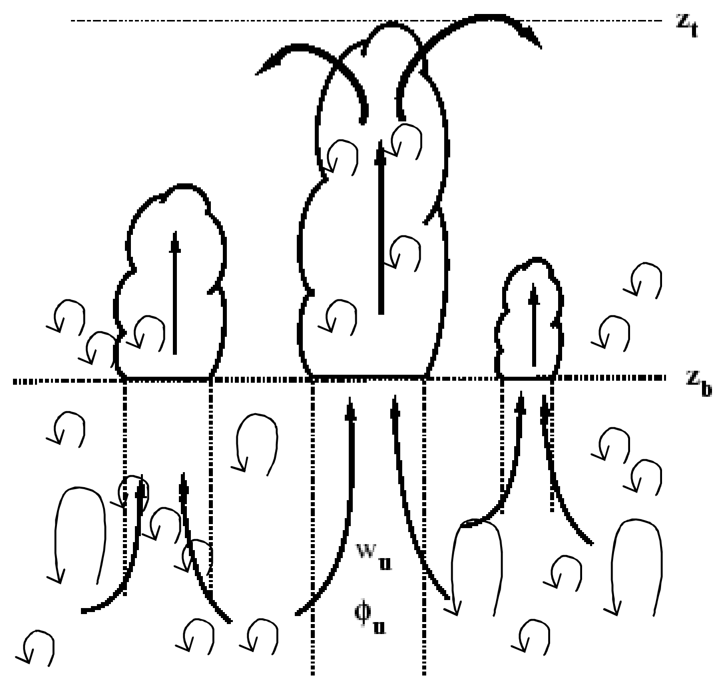
The Idea :

••••

•Nonlocal (Skewed) transport through strong updrafts in clear and cloudy boundary layer by advective Mass Flux (MF) approach

•Remaining (Gaussian) transport done by an Eddy Diffusivity (ED) approach



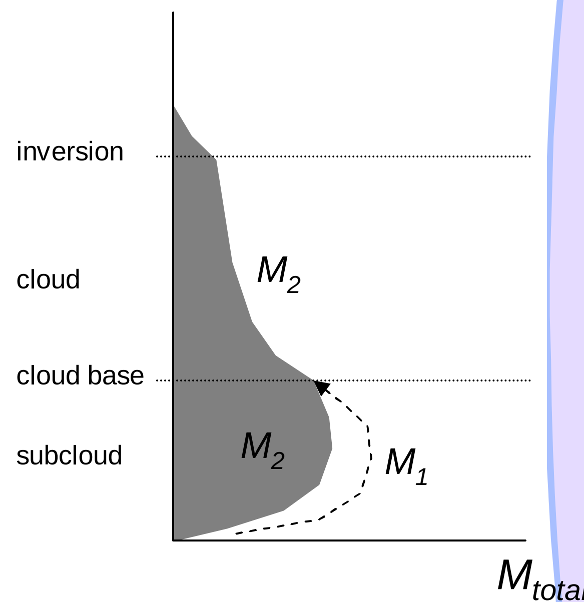


••••

A statistical mass flux framework for organized updrafts

Explicitly model vertical advective transport by strongest multiple updrafts:

$$\overline{w'\phi'}_{PBL} = -K\frac{\partial\overline{\phi}}{\partial z} + \sum_{i=1}^{N} M_i(\phi_i - \overline{\phi})$$



Divide subcloud updrafts into only two groups (N=2):

i) those which will stop at cloud base (i=1)

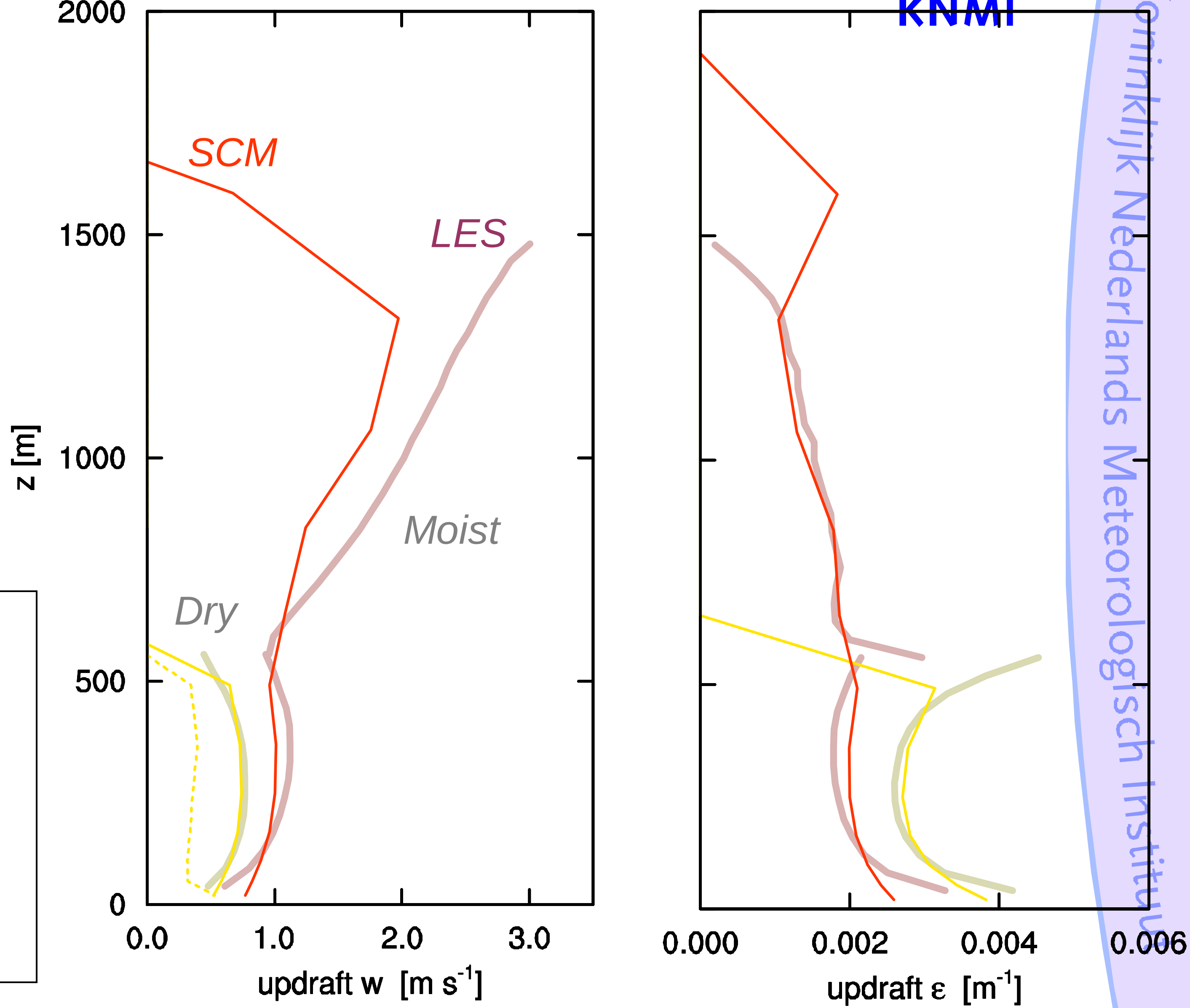
ii) those which will become clouds (i=2)

N=2: two degrees of freedom

the relevant population statistics are represented without 'shooting' too many parcels

Vertical velocity and entrainment

BOMEX



2 SCM runs:

$$\varepsilon_i = \frac{1}{\tau\, w_i}$$

$$\varepsilon_i = \frac{c}{z} + \frac{1}{\tau\, w_i}$$

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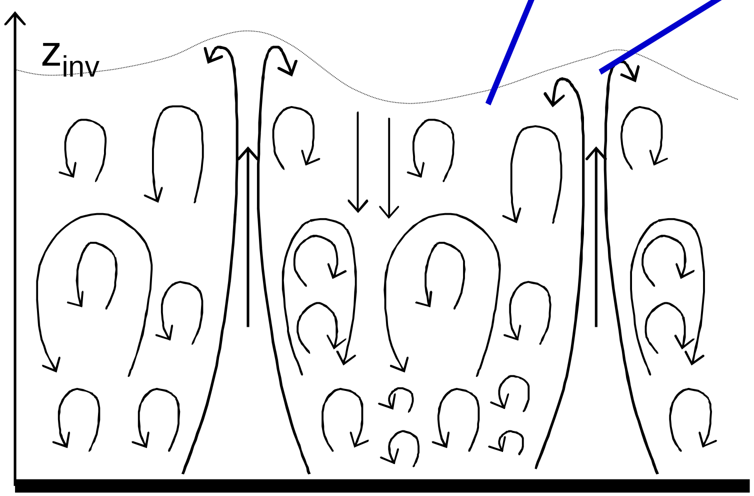
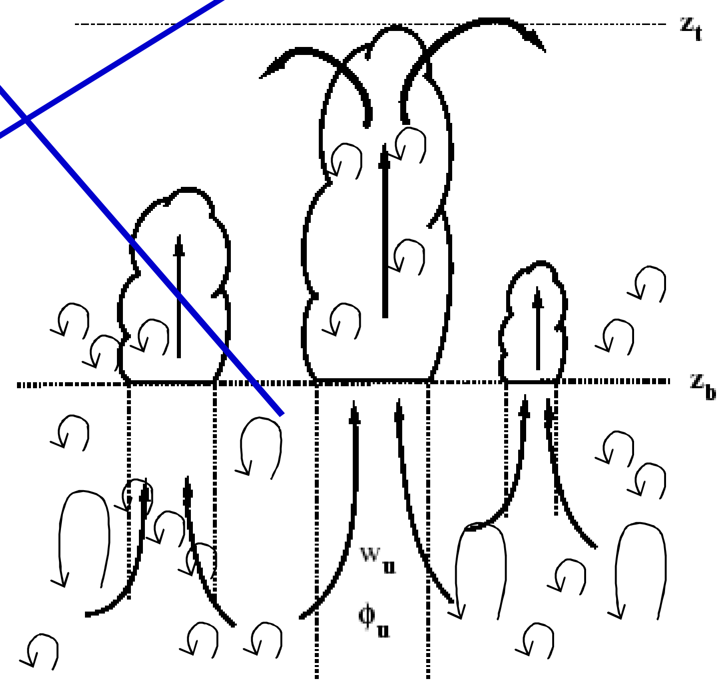
The Mathematical Framework :

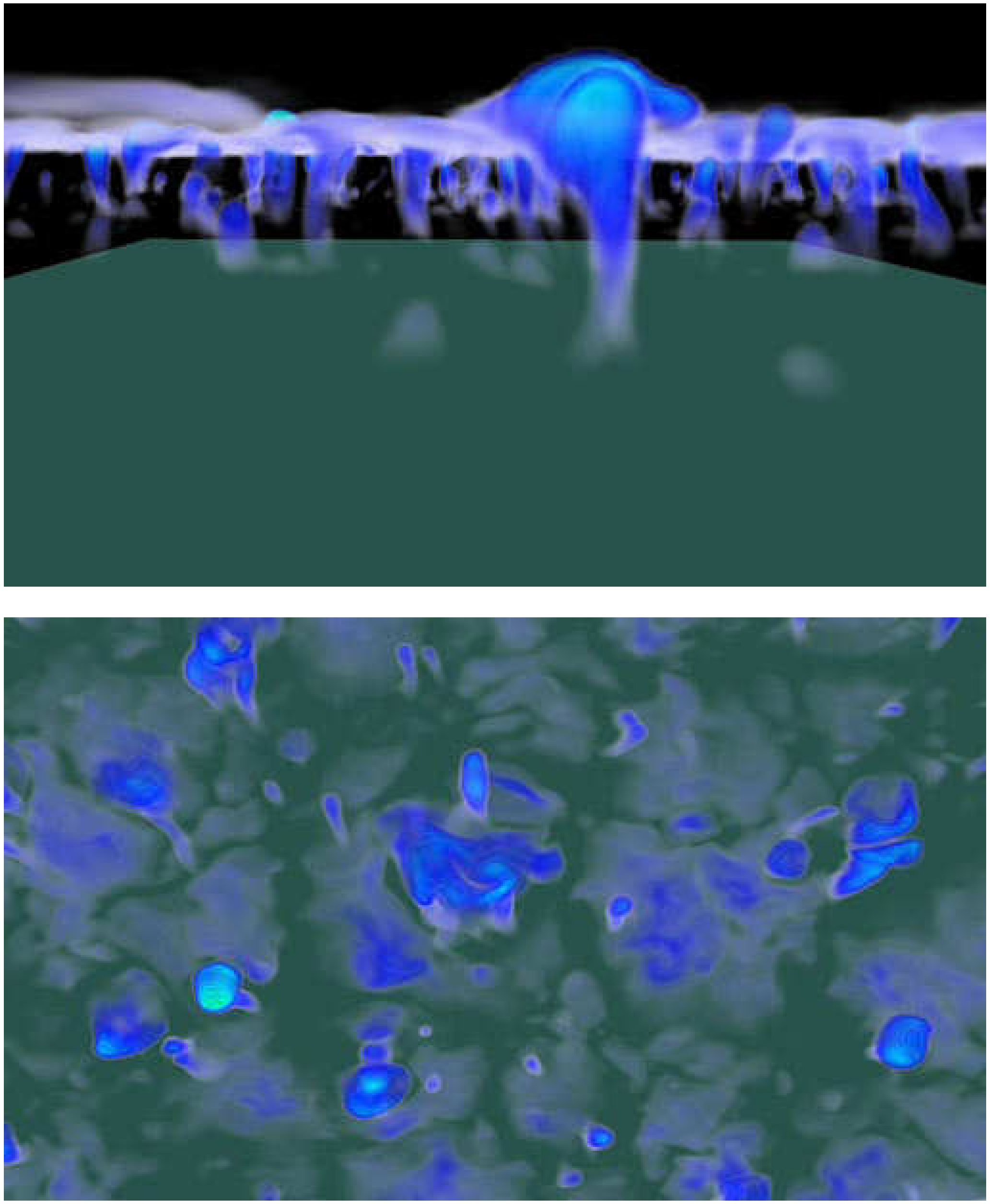
$$\overline{w'\phi'} = a_u \overline{w'\phi'}^{u} + (1-a_u)\overline{w'\phi'}^{e} + a_u w_u (\phi_u - \phi_e)$$

$$\cong \quad -K \frac{\partial \overline{\phi}}{\partial z} + \quad M(\phi_u - \overline{\phi})$$





•ATEX :
Marine
Cumulus
Topped
With
Scu



Courtesy : Dave Stevens ; Lawrence Livermore National Laboratory

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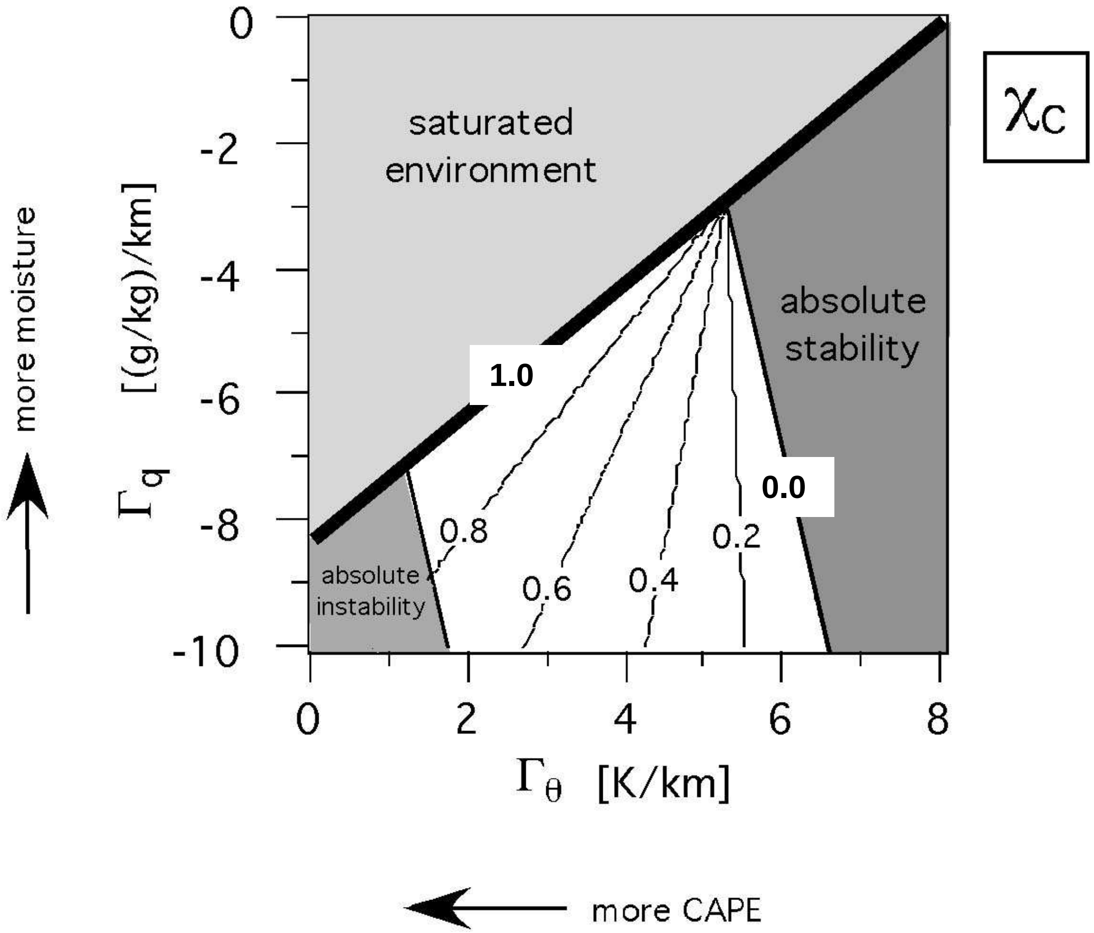
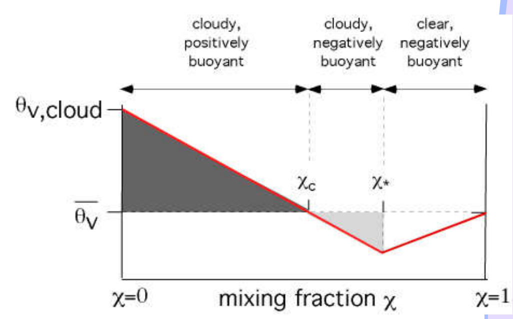
Buoyancy reversal -

Dependency on mean vertical gradients Γ





$$\Gamma_\theta = \frac{\partial \bar{\theta}}{\partial z} \quad , \quad \Gamma_q = \frac{\partial \bar{q}}{\partial z}$$

De Roode, 2004

Conclusions

• Buoyancy reversal does always occur in cumulus

• More active (positively buoyant) cloud updrafts if:

- More CAPE
- More moisture

• Improve parameterizations that only consider CAPE!

Roode, S.R. de, Buoyancy reversal in cumulus clouds, submitted to the J. Atmos. Sci.

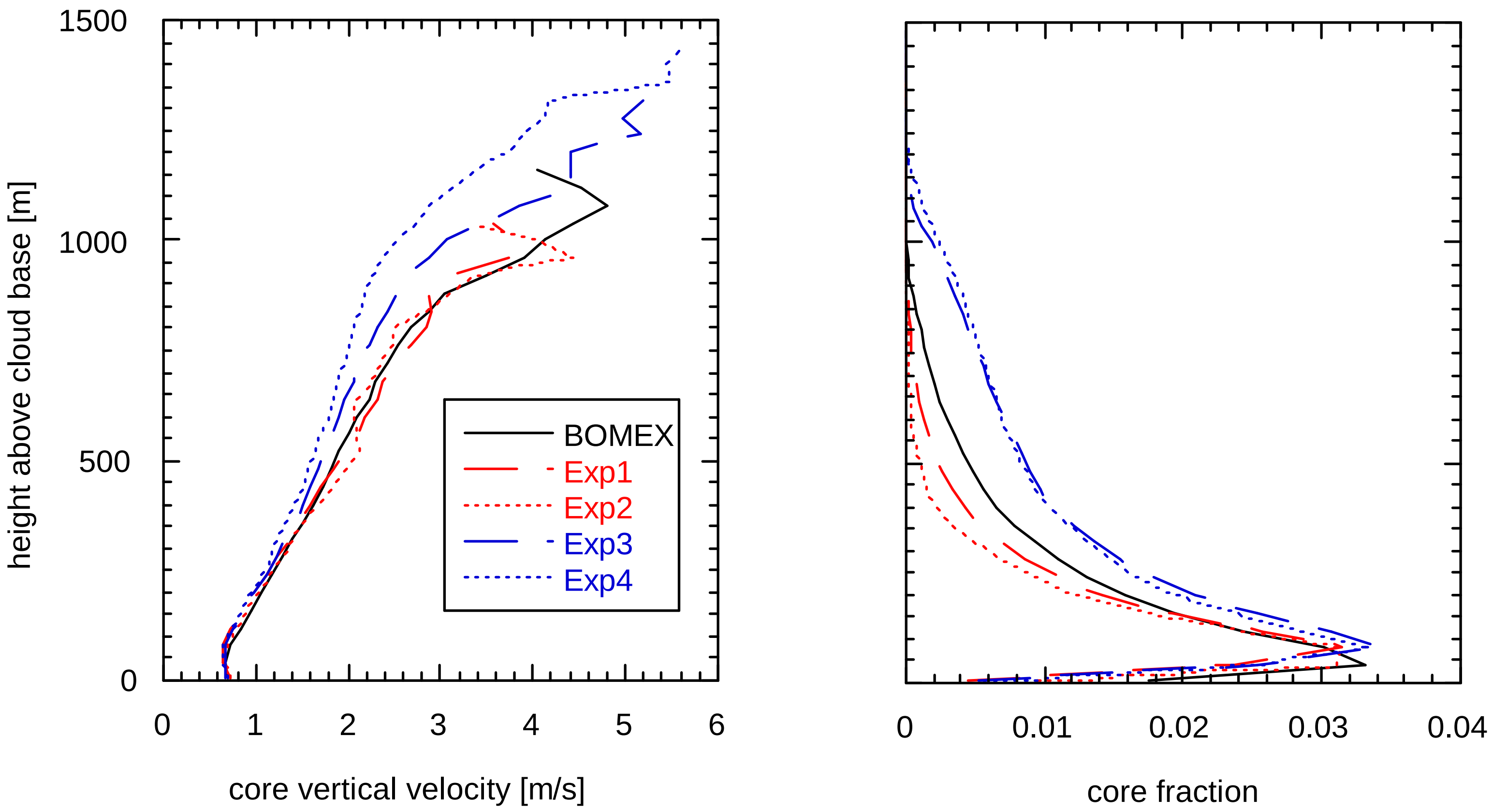
(http://www.phys.uu.nl/~roode/publications.html)

Open Problems:

- Mass flux Closure
- Detrainment (or the mass flux)
- Vertical velocity equation
- Momentum transport
- Connection/Interaction with the cloud scheme
- Connection/Interaction with the dry convection
- Transition to other regimes (Scu / Deep Convection)
- Role of precipitation (RICO)

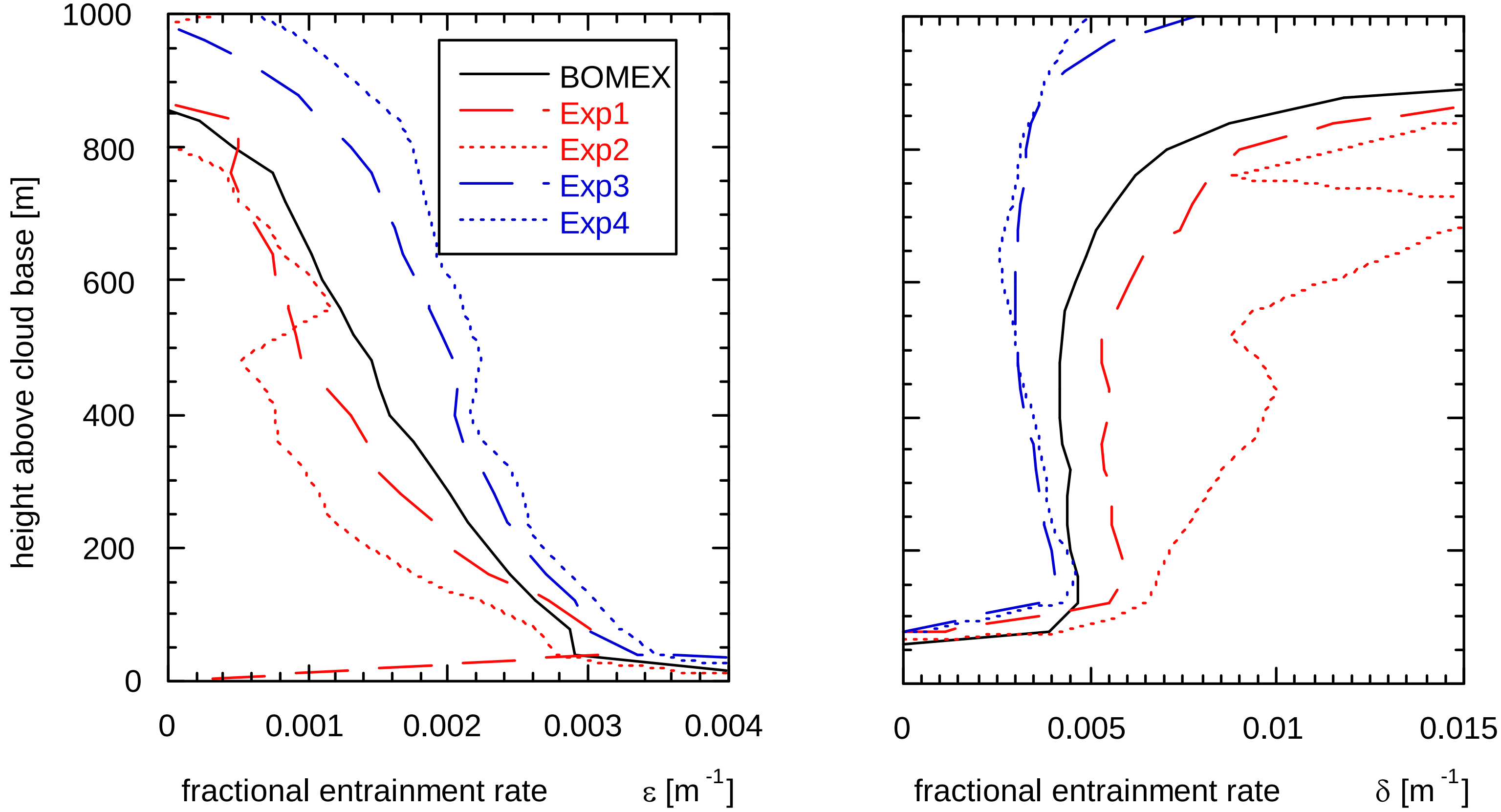
Results for cloud core :

vertical velocity and core fraction



Results for cloud core :

fractional entrainment and detrainment



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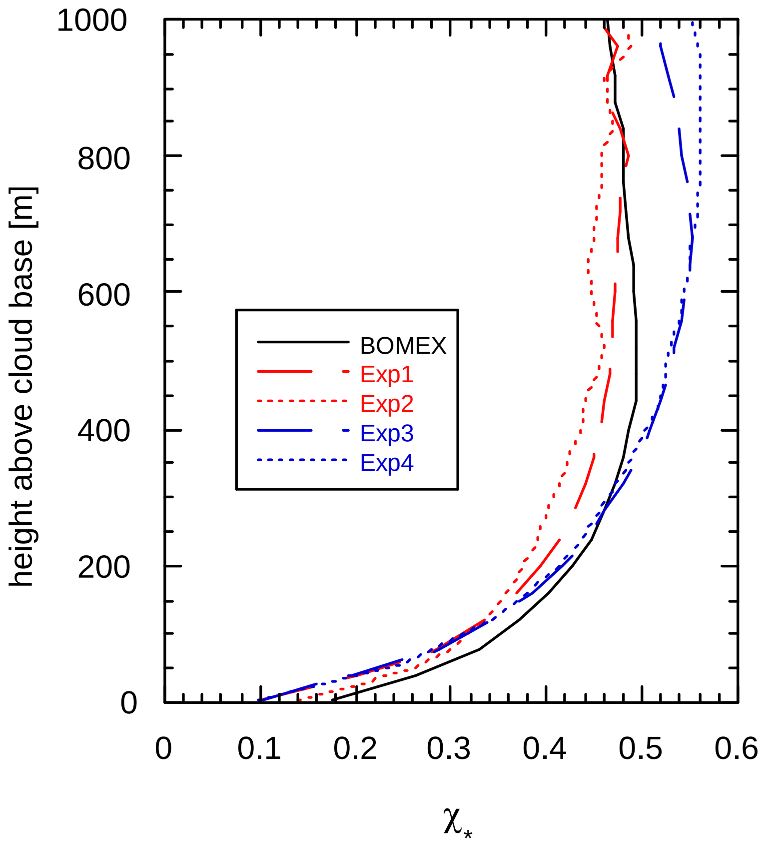
χ_* from LES



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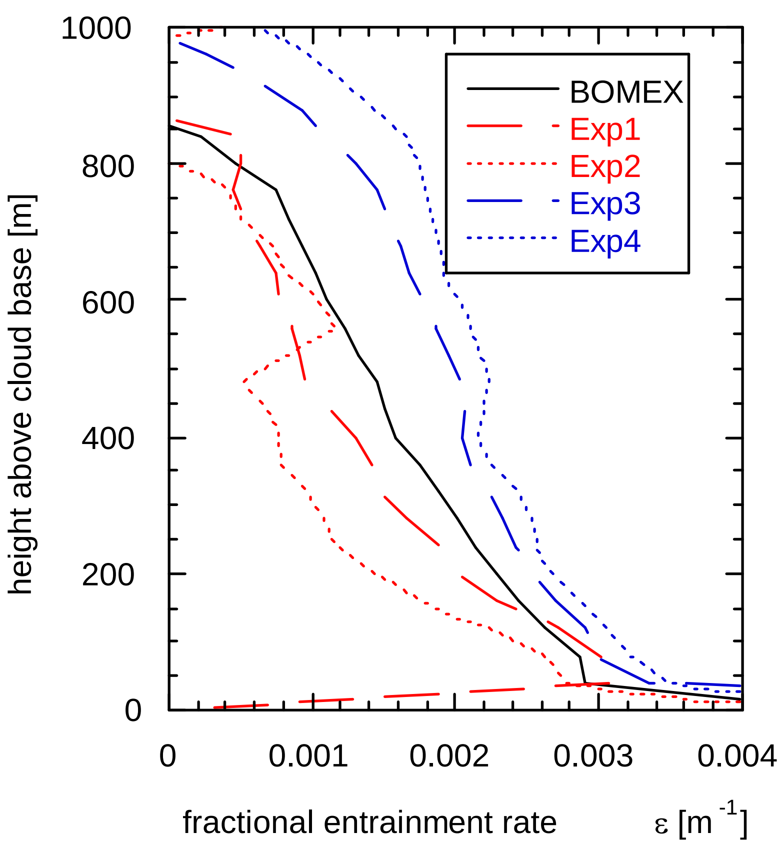
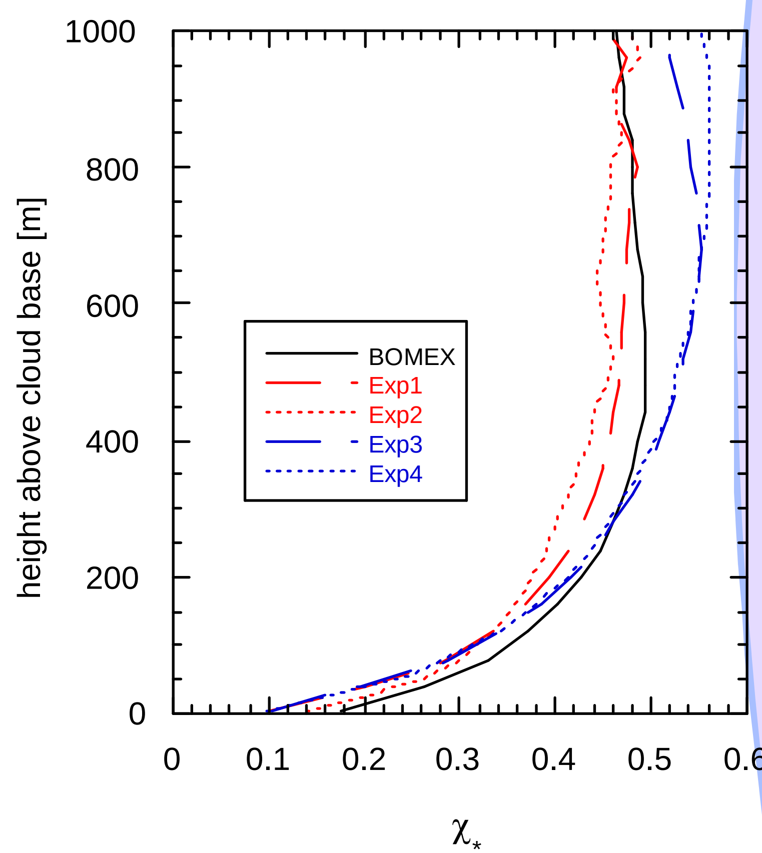
Parameterization: $\varepsilon = \varepsilon_0 \chi^2$

Does it work? Check from LES results.





- **Boundary layer equilibrium**

$$M_b\,(q_{c,b} - \bar{q}) = \overline{w'q'}_{srf}$$

- **subcloud velocity closure**

$$M_b = c w_*$$

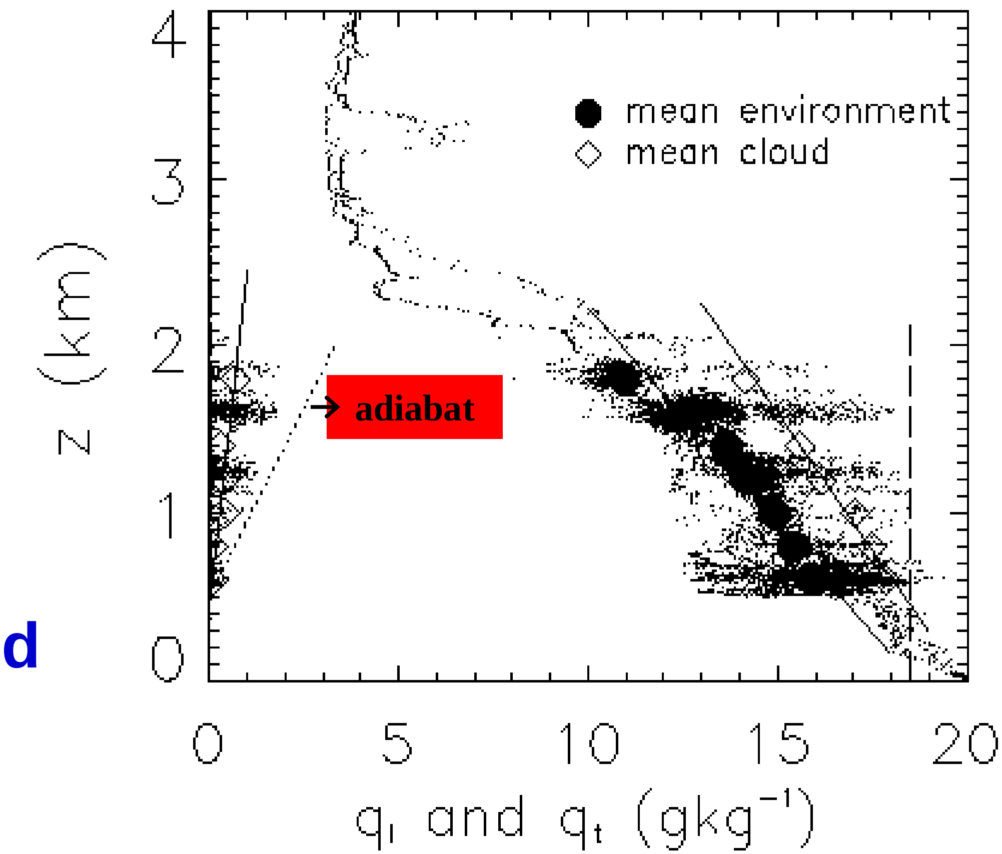
- **CAPE closure: based on**

$$\frac{\partial CAPE}{\partial t} \approx \frac{CAPE}{\tau}$$

….Mixing between Clouds and Environment

(SCMS Florida 1995)

$$ {q_l}\Big/{q_{l,ad}} = 0.3 \sim 0.4 $$



Due to entrainment between the clouds and the environment.

Data provided by: S. Rodts, Delft University, thesis available from:http://www.phys.uu.nl/~www.imau/ShalCumDyn/Rodts.html

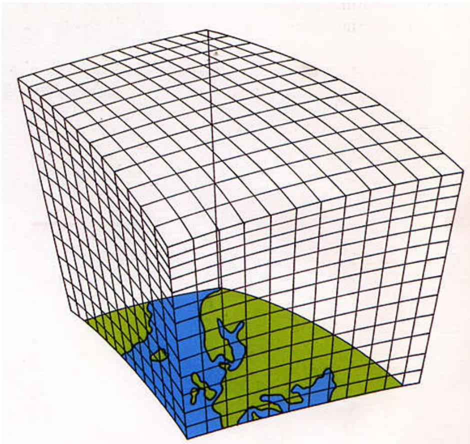
….

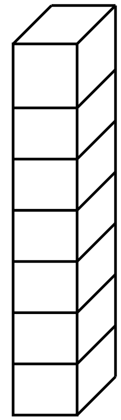
4. Evaluation

of the

Shallow Convection Parametrization

•Methodology:





full 3d model

Single Column Model version

Difficult to isolate and assess the performance of one model component……

Use a well documented case and prescribe the large scale forcing!!

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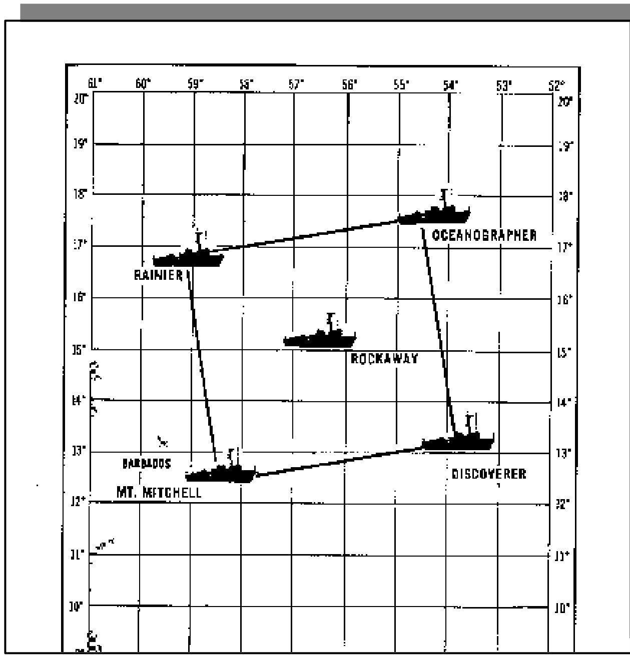
BOMEX Trade Wind Cumulus Experiment: 1969.

(Siebesma and Holtslag JAS 1996)

- **No observations of turbulent fluxes and mass flux, but..**
- **Large scale tendencies measured by a radiosonde array**

BOMEX ship array



$$\frac{\partial\bar{\phi}}{\partial t} = \left(\frac{\partial\bar{\phi}}{\partial t}\right)_{\substack{\text{large}\\\text{scale}}} + \left(\frac{\partial\bar{\phi}}{\partial t}\right)_{\text{subgrid}} \approx 0$$

observed

observed

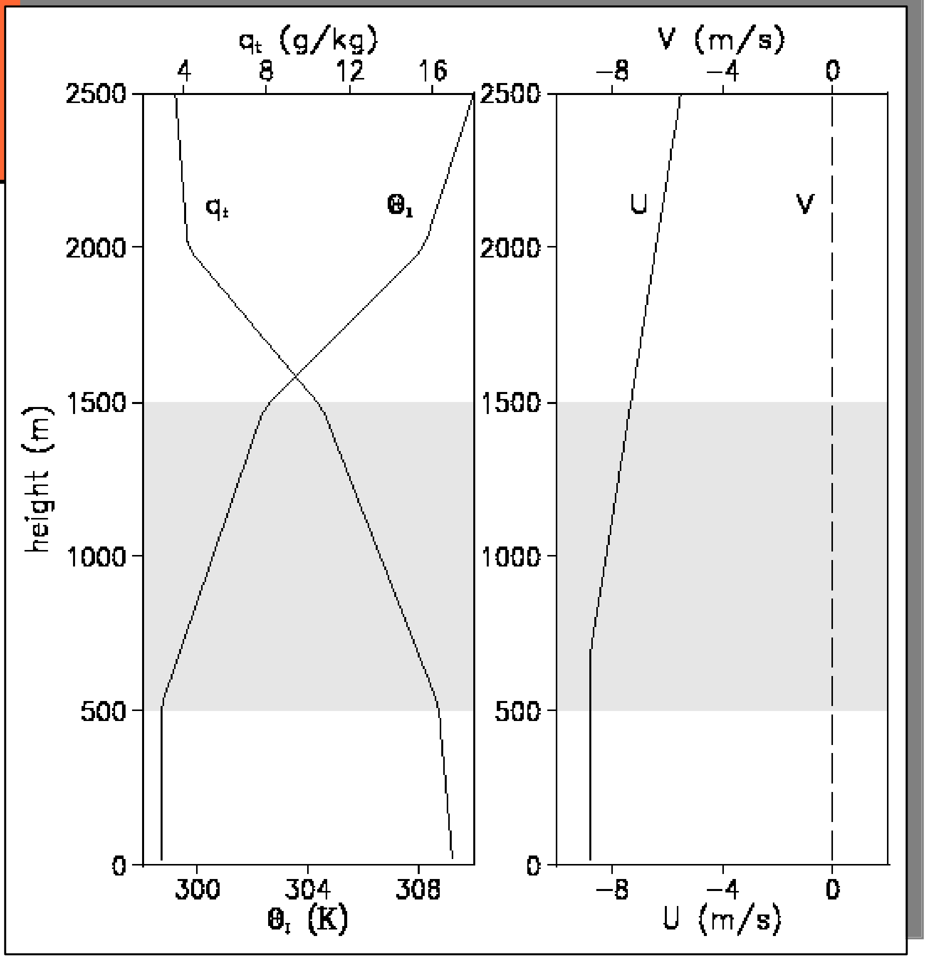
To be simulated by SCM

•ECMWF SCM model 21r3

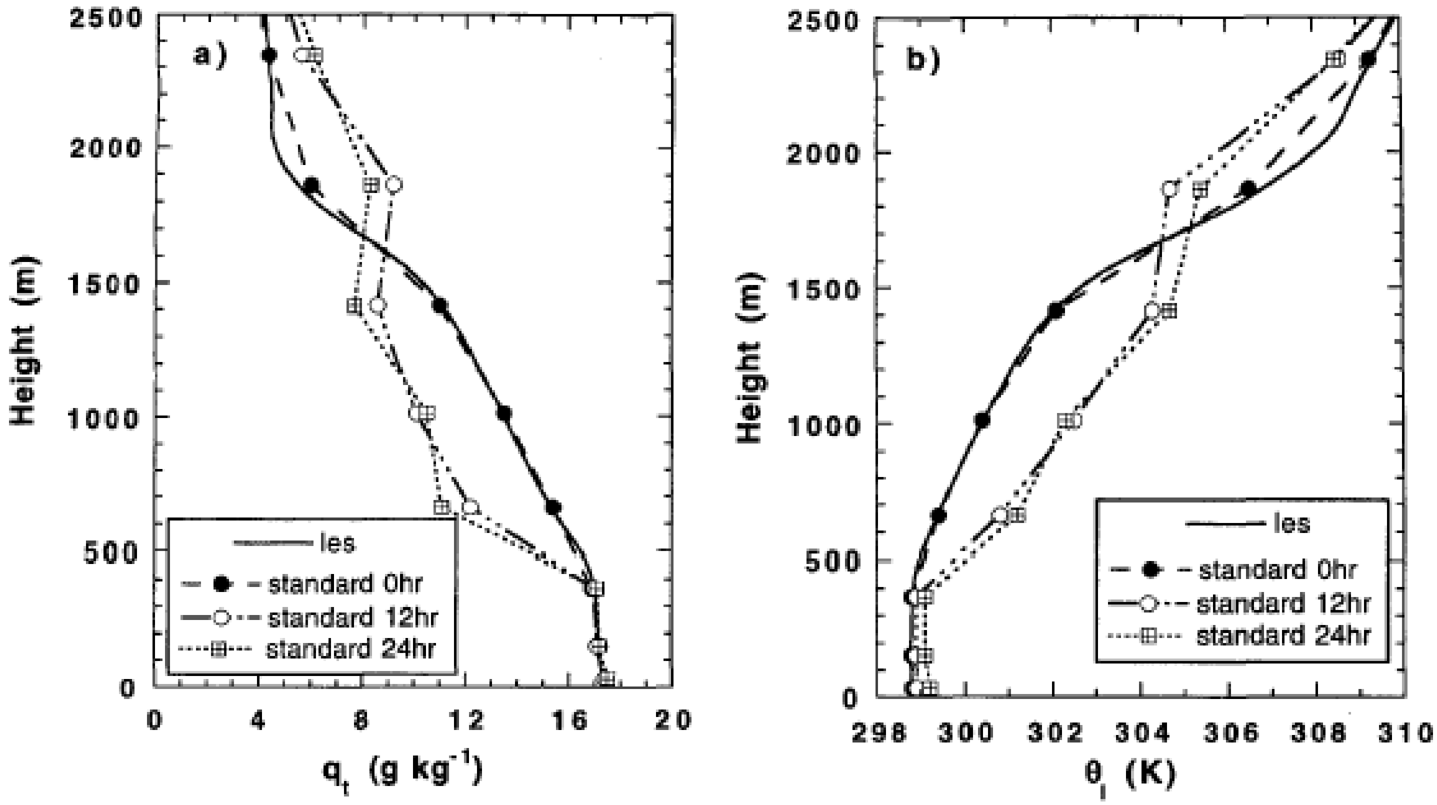
•Initial profiles

•Large scale forcings prescribed

•24 hours of simulation



Is SCM capable of reproducing the steady state?



Too vigorous vertical mixing of q_t and θ_l .

What to do……..?

••••

Implementation simple bulk model: ....

KNMI

1. Updraft Calculation in conserved variables:

$$\frac{\partial \theta_{l,c}}{\partial z} = -\varepsilon(\theta_{l,c} - \overline{\theta}_l)$$

$$\frac{\partial q_{t,c}}{\partial z} = -\varepsilon(q_{t,c} - \overline{q}_t)$$

2. Reconstruct non-conserved variables:

$$\{\theta_l, q_t\} \Rightarrow \{\theta, \theta_v, q_v, q_l,\}$$

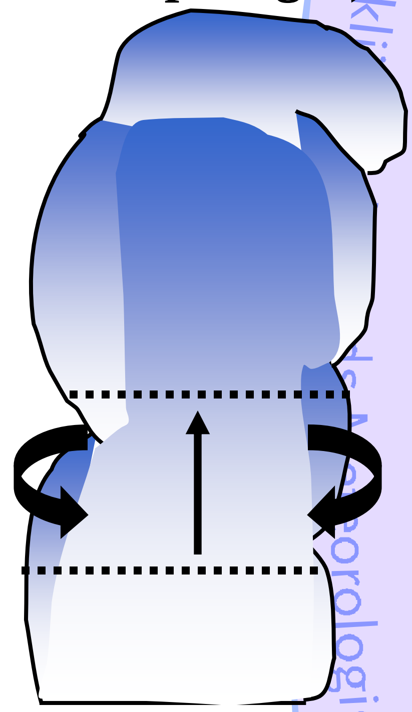
3. Check on Buoyancy:

$$B = \frac{g}{\overline{\theta}_v}\left(\theta_{v,c} - \overline{\theta}_v\right)$$

B>0

continue

Stop (= cloud top height)



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Diagnose $$\varepsilon = -\frac{\partial \phi_c}{\partial z} \Big/ (\phi_c - \bar{\phi}) \quad \text{for } \phi \in \{\theta_l, q_t\}$$

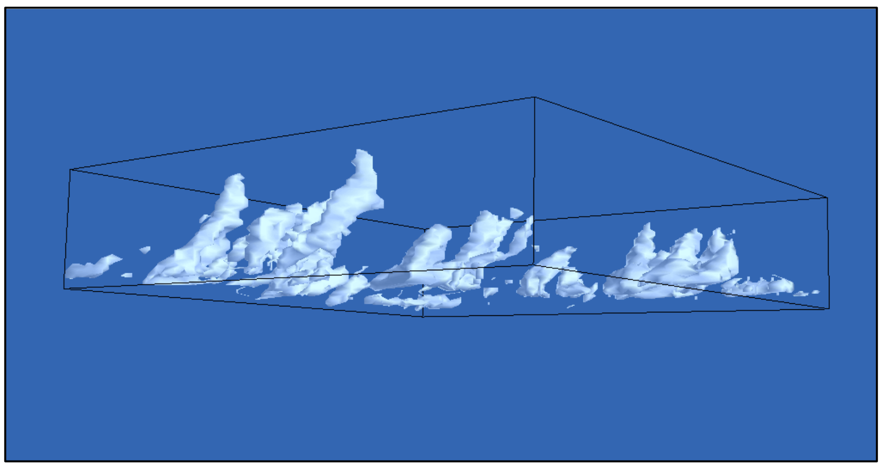
Entrainment factor

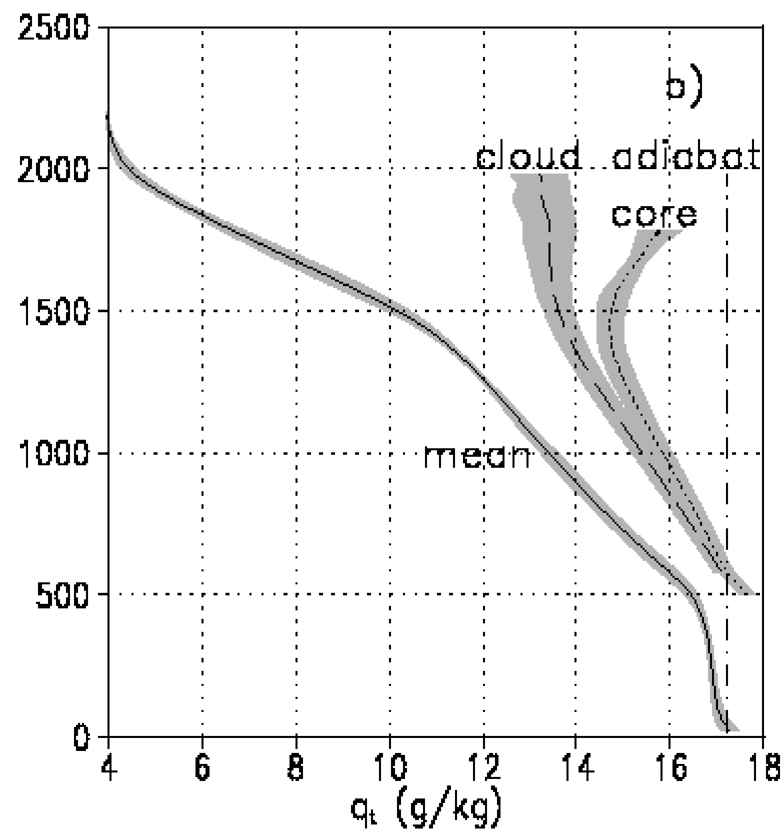
through conditional sampling:

Measure of lateral mixing

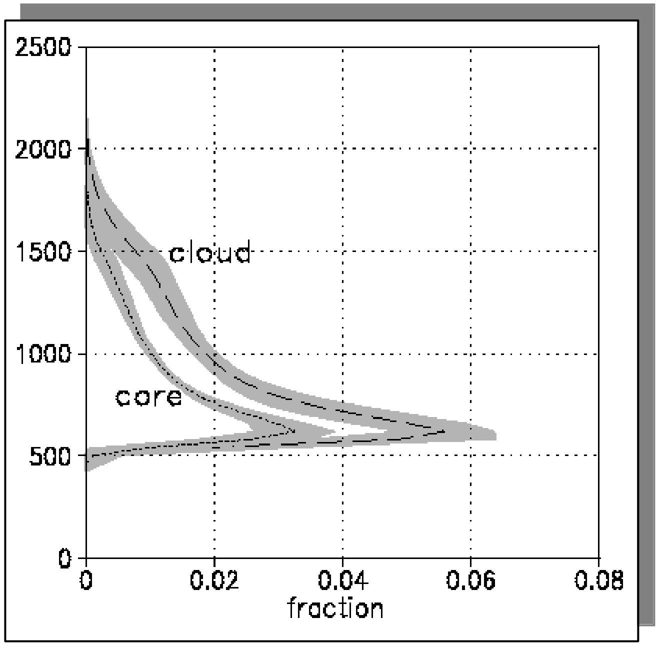
Typical Tradewind Cumulus Case (BOMEX)

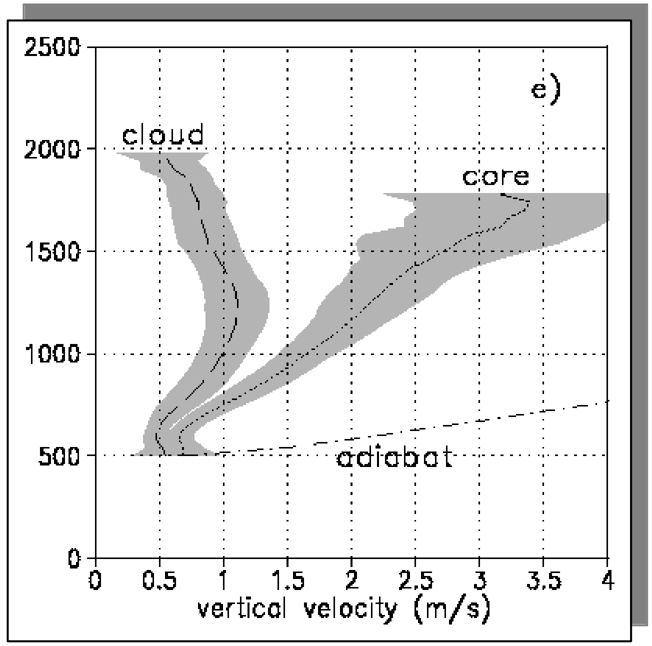
Data from LES: Pseudo Observations





Total moisture (qt =qv +ql)





$$M = a_c \times w_c$$

•Due to decreasing cloud (core) cover

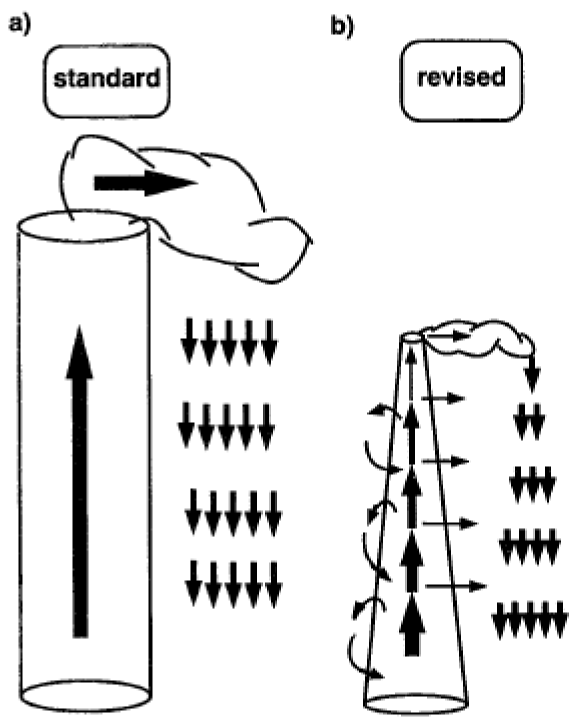
••••

Diagnose detrainment from M and ε

:

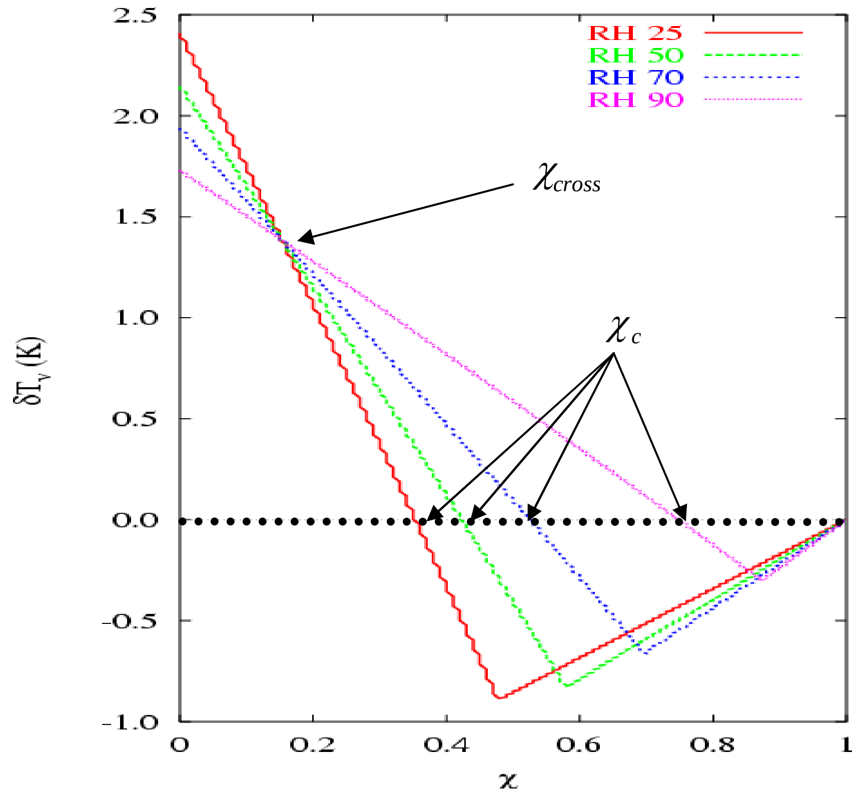
$$\frac{\partial M}{\partial z} = \varepsilon - \delta$$

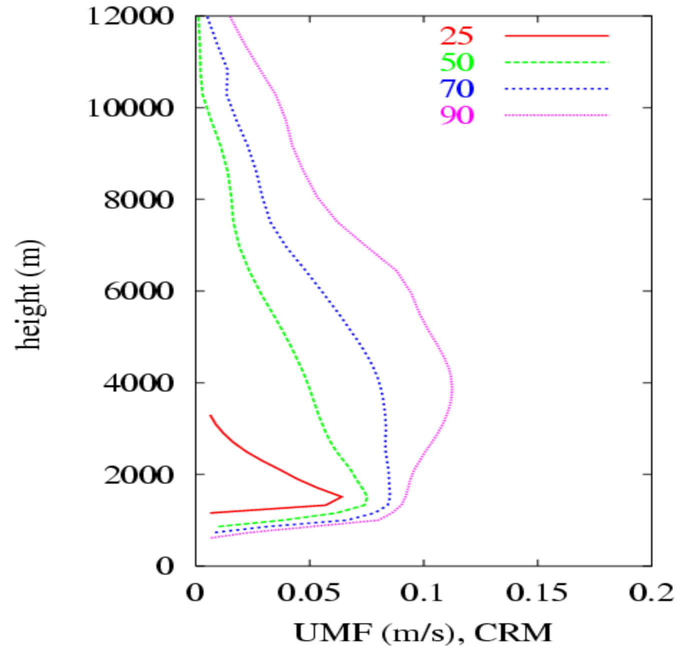
$\varepsilon \sim 2\ 10^{-3}\ m^{-1}$ and $\delta = 3\ 10^{-3}\ m^{-1}$



- **Entrainment and detrainment order of magnitude larger than previously assumed**
- **Detrainment systematically larger than entrainment**
- **Mass flux decreasing with height**
- **Due to larger entrainment a lower cloud top is diagnosed.**

Results for the Relative Humidity Sensitivity Test Case





- χ_c decreases as the relative humidity decreases !

$$\frac{1}{M}\frac{\partial M}{\partial z} = \varepsilon - \delta$$

Looks qualitatively ok!!

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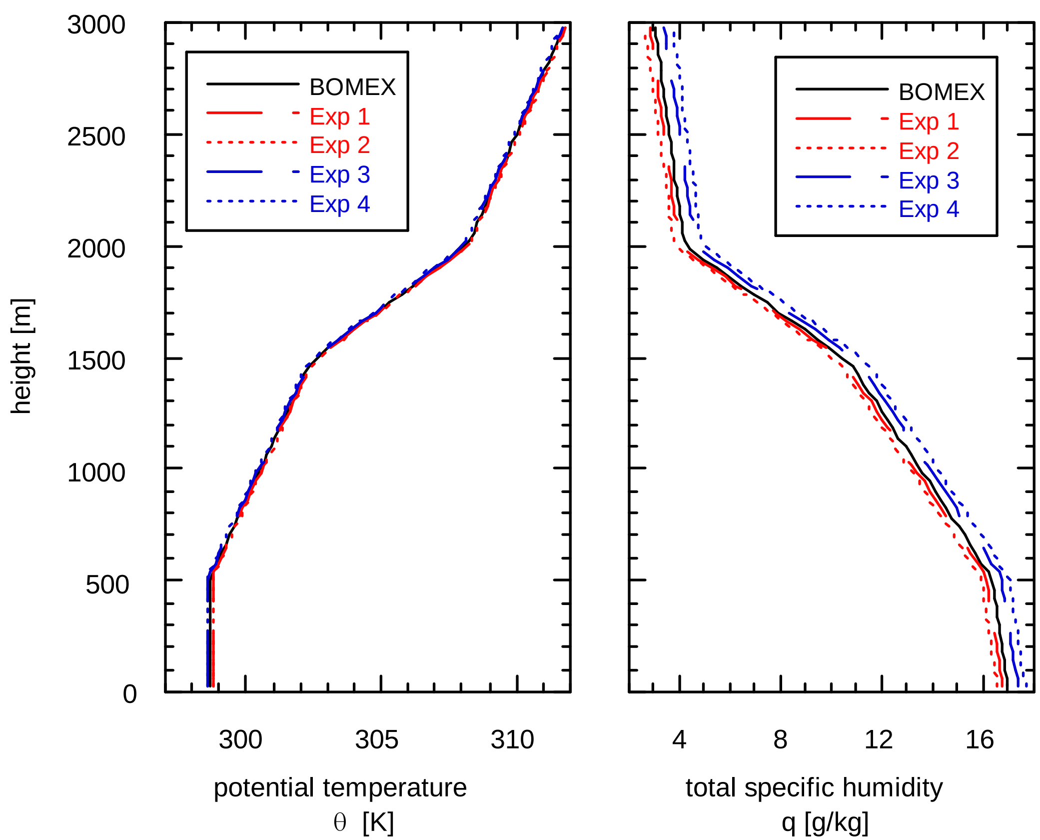
Large-eddy simulation -

The BOMEX shallow cumulus case

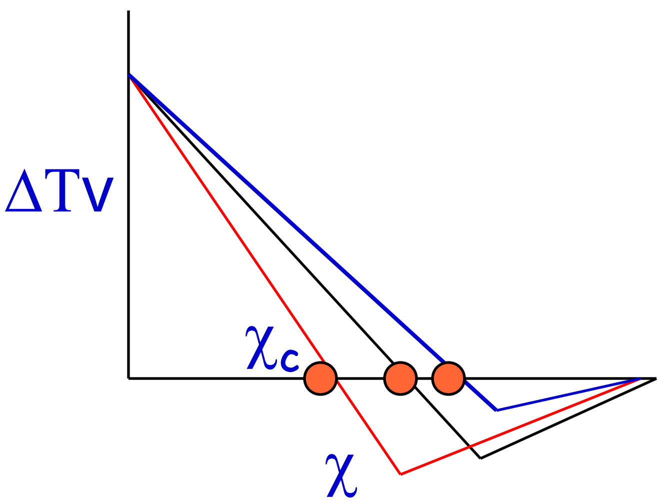


$$\theta_v = (\theta + \delta\theta)[1 + 0.61(q + \delta q)]$$

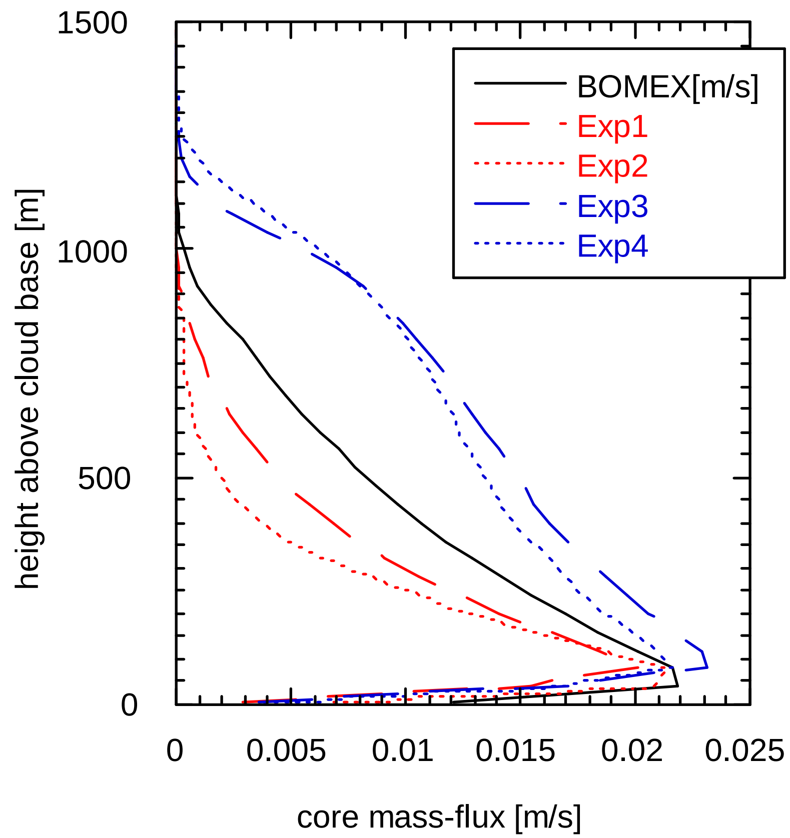
	δθ [K]	δq [g/kg]
BOMEX		
Exp 1	0.04	-0.2
Exp 2	0.07	-0.4
Exp 3	-0.07	0.4
Exp 4	-0.13	0.7

Thanks to: Stephan de Roode

Results for cloud core : mass flux



$$\frac{1}{M}\frac{\partial M}{\partial z} = \varepsilon - \delta$$



Looks qualitatively ok

••••

Conclusions:

•Buoyancy Sorting Mechanism looks "qualitatively ok".

•Thermodynamic considerations alone is not enough to parameterize lateral mixing and hence the mass flux

•Kinematic ingredients need to be included

$$\varepsilon_0 = F(w_{core}, z)$$